Design and Analysis of Production Systems in Aircraft Assembly

by

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ABSTRACT

In complex manufacturing systems such as aircraft assembly, it is difficult to coordinate the design of all the elements that comprise the system to work together effectively in achieving the overall goals. This thesis presents a methodology for analyzing a current production system to understand how the design attributes interrelate and the method to redefine those attributes based on the principles of lean production.

First, a case study on wing assembly comparing five different sites is presented to assess the current state of production system design in airframe assembly. From the case study, characteristics about the aircraft industry are determined as well as the differences when compared to the automotive industry and opportunities for further improvement are identified. A second case study shows how one aircraft assembler attempted to implement the principles of lean production in their plant. This case study presents some implementation issues and discusses the impact of standardization and setup reduction in manually intensive tasks.

Before the design of a system may be changed, the factors that influence the current design must be understood. In military aircraft programs, the procurement policies have a profound impact on how the manufacturing systems are designed and operated. These effects are discussed to provide understanding for the redesign of those policies and to illustrate that manufacturers must design and operate their systems methodically, instead of allowing them to evolve in reaction to cost accounting and procurement policies.

Finally, a generalized methodology is developed for assessing the design of a production system. This analysis assesses how well the different attributes of a system are implemented and how they interact, providing a tool to aid the design of a lean production system.

Thesis Supervisor: David S. Cochran
Title: Assistant Professor of Mechanical Engineering

Acknowledgements

Less than two short years ago, I arrived at MIT in excitement and awe of a prestigious institution at which I would have the honor of working with many talented peers and learn from professors who are leaders in their fields. Looking now at this thesis, I remember not only the research I have done here, but all the learning, mistakes, long nights and friendships made. I am thankful to all those who have helped me along the way, providing a most memorable and rewarding MIT experience.

My first trip to this institution started in despair as my poor planning yielded few potential research projects. To the rescue was of course, Leslie Regan of the ME grad office, who offered much help in finding a research project.

The first meeting with Prof. David Cochran introduced me to a new field. His enthusiasm and perspective on manufacturing motivated me then to start the project and throughout my time here, to approach engineering and problem solving in an entirely new way. I will always be grateful for the opportunities he has provided me and the many talks we have had.

The next encounter I would soon have was with Tom Shields, my sponsor and LAI supervisor. I would not have guessed from this brief meeting that Tom would have such an integral role on my experience here. I am grateful for all his support and continuous feedback.

I still remember my first Factory Operations meeting as I smirked watching my seniors being scrutinized by the faculty members. Little did I know that I too would be subjected to this "academic cleansing" on a bi-weekly basis. To Prof. Timothy Gutowski, Prof. Stanley Gershwin and the rest of the Factory Operations group, I feel lucky to be the only Master's student with regular committee meetings.

As my research assistantship kicked off, I was paired with visiting Prof. Paulo Lima from Brazil. It did not take long to realize that I had found a true mentor, taking whatever time necessary to explain and debate concepts and constantly challenging me with projects.

Venturing into the aircraft industry, I saw many of the challenges required in putting together complex machines of the highest quality and learned many important lessons. I thank the LAI contacts and their co-workers who hosted my stay at their companies and provided valuable advice and insight into their manufacturing systems.

Thanks to the PSD lab for providing me a second home – literally. My fellow PSDer's, Micah, Jorge, Vicente, Jim, Dan, Yong-Suk, Jose, Jochen, Kristina, Alex and Ania made the many times spent together memorable and enjoyable as did my fellow grad students John, Yu-Feng, Melissa, Mike, Derek, Corey and Jamie. Thank you for all your help and good times; best wishes on your future endeavors.

Looking back, I see the loved ones who have supported me throughout, and who may draw this Canadian home. Thanks to the "Gang," Albert, Mike T., Mike L., Aidan, Hannah, Maureen and Wynne for their enduring friendship and brightening visits. With even more visits by Sanjay, Rob, Matt and emotional support from Gina, I never felt far from home.

My deepest appreciation goes out to my family who has always supported me. I feel lucky to have a brother who has shared the excitement and problems throughout our adventures with a special bond. I am grateful to my mother and father for their valued teachings on life, encouragement in education and their uncompromising love and support.

Finally, I thank God for His many blessings and hope that He continually guides my path.

– Andrew Wang

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Chapter 1: Introduction

Throughout history, transformations in industry have often been stimulated by a "crisis situation" or need, followed by a technological advancement to satisfy it. As military spending decreases from that of the cold war, aircraft companies and the military alike have concentrated efforts on delivering the highest amount of defensive capability with the lowest cost. Part of this strategy is to reduce the manufacturing costs but marginal improvements in operating efficiency would not be enough. However, through studies in the automobile industry, it has been found that very significant improvement in cost, quality, and throughput time may be achieved through a different approach to manufacturing. This approach originated from the Toyota Production System (TPS) [Monden, 1998] and has since been named "Lean Production" [Womack et al., 1990]. Many other industries have taken note of TPS and have adopted their methods with varied success. This has spawned many consulting and research activities to teach the principles and tools of TPS so that companies may be successful in its implementation.

This thesis focuses on the implementation of lean production in airframe assembly through analysis of the production system design. With its application, it is hoped that the Air Force can maintain high quality defense capabilities in the face of decreased military spending. With these methods applied to the private sector, the opportunity for marked increase in manufacturing efficiency and capability may give companies the advantage they need to compete with domestic and foreign competitors.

1.1 Chapter Summaries

To provide a succinct description of the organization of this thesis, each chapter is briefly summarized. It also outlines the flow of ideas and provides the context for which each chapter is written.

2. Background – Literature Review

This chapter describes briefly the development of lean production and how it has changed the way production systems are being designed and how businesses are being run. Some background on aircraft assembly is presented to set the stage for the need to change the manufacturing methods in the industry. Current research on these topics by the Lean Aerospace Initiative (LAI) and the Production System Design (PSD) laboratory are outlined and the contribution of this thesis is stated.

3. Wing Assembly Case Study

This chapter presents a case study comparing the wing assembly operations of five sites to assess the current state of aircraft assembly. Observations of the assembly operations are made and data on throughput time, quality, labor hours and delays are presented to characterize the industry.

4. Introduction to PSD Analysis

To further understand what lean production means, the PSD decomposition [Cochran, 1998] is proposed as a model. This section explains the PSD decomposition – an axiomatic design decomposition of a generalized manufacturing system – in more detail. This theory will act as the basis for much of the analysis in the chapters that follow.

5. PSD Analysis of Wing Study

This section is the analysis of the wing assembly case study using the PSD decomposition as a framework. It provides further insight into the problems observed in the system and outlines an approach to deal with these issues. The PSD decomposition, applicable to a wide range of industries, is discussed with respect to how it specifically applies in a low volume, low process capability, highly manual assembly environment as in the aircraft industry.

6. Experiences in Lean Implementation: B-2 Case Study

The B-2 case study serves as an example of setup reduction and standardization in manual work content and the impact on the total production system design. The results of these changes, the methodology and the lessons learned of the implementation will also be further discussed. The purpose of this chapter is to show how some of the recommendations have been put into practice and how they have impacted the system.

7. Beyond Factory Operations

One of the barriers identified in lean implementation is the procurement policy issue in military programs. The impact of these policies and how they have influenced production system design and operation is presented. An axiomatic design decomposition of how manufacturers respond to procurement policies is used in contrast with the decomposition of a lean system. Recommendations on rethinking the procurement policies to promote lean production are made.

8. Production System Design Evaluation

This chapter presents the Production System Design Evaluation Tool developed based on the PSD decomposition and from the analysis used in the wing assembly case. The motivation for such a tool, the methodology in developing it and how it is applied will be presented.

9. Conclusions

Summarizes the conclusions and recommendations made throughout the thesis.

Chapter 2: Background – Literature Review

This chapter describes briefly the origin of lean production to describe a system design and how the system design changed the way businesses are being designed and run. Some background on aircraft assembly is presented to set the stage for the need to change the manufacturing methods in the aircraft industry. Current research topics in Lean production and production system design by the Lean Aerospace Initiative (LAI) and the Production System Design (PSD) laboratory respectively are outlined. The contribution of this thesis is also stated at the end of this chapter.

2.1 Lean Production – The Toyota Production System

Lean production – coined by the International Motor Vehicle Program (IMVP) in their study on the auto industry [Womack et al., 1990] – has caught the attention of manufacturers all over the world. The manufacturing system design represented was developed by Toyota [Cochran, 1994] from the 1940's to the 1970's [Monden, 1998] has since been displayed, taught, studied and even implemented widespread across many industries and countries. In operations management books, TPS is being referred to as "Just in Time" manufacturing [Spearman and Hopp, 1996]. The benefits reported in the automotive industry [Womack et al., 1990] have been astounding with claims of improved quality, lower production costs, shortened delivery and product development time and greater flexibility.

2.1.1 Development

It was not until after the oil crisis of 1973 that the industrial world took note of Toyota Motor Corporation's manufacturing prowess [Shingo, 1989]. However, the principles of TPS developed from the 1940's during a time when Japan was in a post-war rebuilding stage and resources were scarce. At that time, Japan's automotive industry was insignificant and labor productivity was one ninth that of the U.S. [Spearman and Hopp, 1998]. Because Japan's automobile market was small, they could not compete with just the economies of scale realized by mass production. Toyota concentrated on reducing costs by eliminating waste and producing a greater variety of vehicles in smaller numbers with the shortest possible lead time. The challenge was to produce this wide range of vehicles in a regular production routine with very limited resources and without holding large levels of inventory. Toyota responded to this challenge with the development of a production system design that rests on two pillars, Just-in-time, and autonomation (Jidoka – automation with a human touch).

2.1.2 Principles

The idea of just-in-time came from Kiichiro Toyoda; Taichi Ohno's implementation of JIT came from the observation of American supermarkets where customers took the products they needed, when they were needed and in the amounts that were needed. The shelves would then be replenished as they were being emptied, signaling orders in response to actual customer demand. In the manufacturing version of this analogy, the downstream customer takes only the parts needed from standard inventories and upstream sub-systems are signaled to produce based on what is taken. To implement the pull systems, Kanban – the Japanese term for card – were used to advance parts for assembly and to signal upstream production as material is consumed. To avoid large amounts of inventory, the throughput time and response time of the manufacturing system was minimized by production leveling, product flow oriented layouts and single piece flow. Autonomation allowed further cost reductions through separation of worker and machine, leading to cellular manufacturing [Black, 1991].

To level production and thereby achieve low levels of inventory, the production schedule must first be very regular, both in terms of volume and product mix. Toyota translated total demand over a month to a takt time, which was the time interval that vehicles are produced. This takt time paced production to ensure that processes did not work ahead and then fall behind, causing surges that require inventory. Because Toyota produces a wide range of vehicles, leveling the different product types has a great impact on the ability to reduce inventory. Instead of producing large batches of each product type at a time (1000 A parts, 2000 B, 1000 C), parts are leveled so that model mix is maintained over the smallest time frame possible (10 A, 10 B, 10 C, 10 B). To achieve this mixed model production, setup times were reduced dramatically through single minute exchange of die [Shingo, 1989]. This was a unique approach to reducing the cost of set-ups, which was traditionally minimized by setting optimal lot sizes, assuming set-up time was constant.

In product flow oriented layouts, there may be more total machines than in a job-shop layout. To reduce the number of workers necessary, workers must be able to run several machines [Cochran, 1998]. To do this, the machines would have to run independently, automatically stop, and detect errors, eliminating the need for machines to be monitored. Operators would typically load a machine (a task difficult to automate) and move to the next machine as the machine cycles automatically and unloads the part (easy to automate task). These characteristics describe automation with a human touch – autonomation. In combination with cross-trained operators and standard work routines, cellular manufacturing was developed which added volume flexibility and improved utilization of workers [Charles et al., 1999].

In addition to some of these innovations, Toyota also applied common sense ideas with exceptional execution. The Japanese term Kaizen, refers to the continuous implementation of small improvements [Monden, 1997] towards the goals of zero defects and total waste elimination to achieve a given takt time with a minimum of labor. Toyota fostered the philosophy of eliminating all root causes of problems so that they never cause another disruption or defect. Although stopping to correct all problems as they occur is very disruptive, it eventually improves the predictability of the system. Ohno identified seven wastes, overproduction, delay, transport, processing, inventory, wasted motion and the waste of making defective products. Further improvements followed the application of 5S, which refers to a clean and ordered workplace with all unneeded materials, tools, equipment, parts and documentation eliminated. With Kaizen applied diligently to these basic ideas, great improvements in quality, cost, timeliness, work environment and safety were realized.

Innovations of TPS extended beyond the factory to product development, supplier relations, marketing and labor relations. Lean product design involves changes in leadership, teamwork, communication and simultaneous development [Womack et al., 1990]. The commitment to make design decisions early in the process and by placing emphasis on manufacturing helped to decrease development time and ensured that designs could be produced. Instead of "pitting" suppliers against each other to get the best price, Toyota established long term relationships with suppliers and worked with them to improve quality and decrease cost. To establish confidence in production rates, considerable efforts are put into market research, maintaining customers, and even using aggressive sales techniques when necessary [Womack et al., 1990]. Toyota also improved the effectiveness of the workforce by guaranteeing lifetime employment to allow continuous improvement to proceed without the fear of loss of jobs. Perfect attendance programs and work teams were also developed to minimize production disruptions.

TPS, JIT and lean production have been written about and discussed for many years but companies trying to apply these techniques have encountered many challenges. Although the techniques of TPS were developed since the 1940's, research still continues in this area to develop structured methodologies to explain the principles of TPS and how to implement them. There is also particular interest in investigating how the techniques work in industries where conditions may be different. Factors considered have been volume, customization, complexity, culture, amount of automation, predictability of demand and distance to suppliers. More than anything else, observations of TPS have prompted industries and researchers to realize that traditional ways of doing business must be completely rethought, where every previous assumption is questioned in order to develop more competitive production systems.

2.2 Aircraft Assembly

This section provides some background on the aircraft industry. Although the wing assembly case study in chapter 3 provides current observations into aircraft assembly, some of the history of the aircraft industry is presented to understand the reasoning why these systems have evolved to their current states.

2.2.1 Development of Assembly Methods

When the airplane was invented, the structure was made mostly of wood with fabric coverings and wires. Early craft producers employed artisans who produced individual parts – an approach referred to as piecework [Simonson, 1968]. As aircraft production increased, assembly line techniques were used (as rates approached one aircraft per hour). Large machines were employed, doing operations on entire subassemblies. To decrease the number of rivets required, spot and seam welding was used. Rivet holes were also made during the blanking of sheet metal parts. Many unskilled workers were also employed and because of the production rate, they only had a few operations to perform over and over again – such as to install 9 fasteners in one specific area of each plane [Sherman, 1992].

By WWII, aircraft were already built mostly of sheet metal, with other parts from forgings, castings, extrusions and bar stock. The most common metals were aluminum alloys, as are still today. To produce large sheet metal parts with complex shapes and tight tolerances was and still is very difficult. In the design stage, these shapes were "lofted," a process used in ship hull design where control points were defined and wooden or metal slivers were slid through guides to obtain the curves. Plaster molds of the part – male and female were produced which became the "masters" from which tooling and jigs were built. The actual solid model captured the final engineering specifications – the drawings only had the nominal dimensions. By 1995, Boeing designed the first airplane, the 777 entirely using electronic means. Instead of the physical models, computer generated solid models were used to design the tooling and jigs.

Increasingly, sheet metal parts are being replaced by machined extrusions for the internal structure to allow interchangeability of parts. Skins are still often sheet metal but composites are being used more. Composites offer advantages in strength and weight but are often very labor intensive. Titanium is also used in areas with high thermal stresses. Despite these advances, modern airframe assembly still has characteristics of craft production methods. Fitting large parts/assemblies together in precision jigs often requires trimming or shimming operations because the large compliant parts are unable to hold the dimensions necessary.

Although aircraft are continually being upgraded with the insertion of new technological advancements, the time frame for these improvements are quite slow in the airframe sector. Fine [1998] estimates major technological advances in airframes occurring roughly every 10 years compared to every 3 years in electronic controls. In addition, commercial aircraft have had the same configuration for many years and "no change in airframe design is foreseeable in the medium term" [Pavaux, 1995]. With airframe designs that have such long life cycles, improvements made in the assembly process will have a long return period and so are very valuable. This presents an additional motivation to study how to make these operations "lean".

2.2.2 History of Aircraft Industry

Although entire books have been written on the history of the U.S. aircraft industry and the factors that have shaped it, the material presented here is an abbreviated treatment with highlights of points from *"The History of the American Aircraft Industry"* [Simonson, 1968].

After the invention of the airplane by Wilbur and Orville Wright in 1903, the airplane received very little attention by industry before the war. By 1915, the number of airplane patents issued hindered the manufacture of airplanes since lawsuits would be inevitable. This state may have continued for much longer if not for the sudden demand for warplanes as the U.S. entered the war in 1917. At that time, some aircraft (about 2500) were being built for foreign orders but with the new demand from the Navy and Army Air Corps, the industry output would have to increase by ten-fold, and as quickly as possible. This increase would require immediate expansion of existing facilities and the use of the automobile industry as well. To alleviate the problem of lawsuits from patent infringement, the military drafted a patent licensing agreement which stated that all manufacturers for the government would have use of the existing patents and the government would pay the licensing fees as part of the price of the aircraft. To integrate other industries, the government would supply detailed designs for any part or machine ordered, and aircraft manufacturers began to teach their methods to the automobile industry. As the aircraft industry transitioned to full production in a cooperative environment to prepare for the war, it could not have done so without facilitation by the government and the newly established procurement policies.

By 1918, 14,020 aircraft were produced but orders dropped sharply after the war. Again, the government intervened and passed the AirMail act in 1925 to stimulate civil aviation. Further acts followed allowing greater spending by the post office and military for aircraft. Civil aviation gained popularity after Lindbergh's inspiring trans-Atlantic flights in 1927. Sales went from 21.2 million in 1927 to 71.2 in 1929, more than tripling. This promising and seemingly booming industry soon slowed in the 1930's due to the depression and sales dropped to 26.5 million in 1933.

In 1940, Roosevelt called for 50,000 aircraft causing a change from job shop to assembly line techniques of Ford. Ford in fact became a major contractor and established a plant at Willow Run to produce B-24s. By 1944, this one plant accounted for almost 10% of all U.S. aircraft in poundage. In March of that year, the production rate reached almost 1 plane per hour - 453 airplanes (B-24's) in 468 hours [Sherman, 1992]. Mass production techniques were now being used to take advantage of economies of scale to decrease cost. Again, demand far exceeded capacity so Ford again enjoyed the prospect of producing as many planes as possible.

From this brief account, it is obvious that aircraft production is highly dependent on military demand, up to 60% for USA and UK in 1986 [Todd and Simpson, 1986], falling to 37% by 1998 [AIAA, 1998]. This demand has also been characterized with a wave-cycle model, with aircraft production peaking first during WWI, then during WWII and since has oscillated depending on strategic balances in the face of threats to national security as shown in Figure 1. The combination of the surging demand and the large dependence of the aircraft industry on military orders caused great disruption to the industry. In downturns, many companies without commercial business are forced into bankruptcy while the government has to maintain the main contractors with a minimum of orders. Lately, the merger of Boeing and McDonnell Douglas illustrates the combination of military and commercial capabilities to protect against downturns in either business. As an aircraft manufacturer, to set a strategy of maintaining competitiveness in slow periods, observation of how Toyota was able to continue profits after the 1973 oil crisis through their production system would stir great interest – as it has.

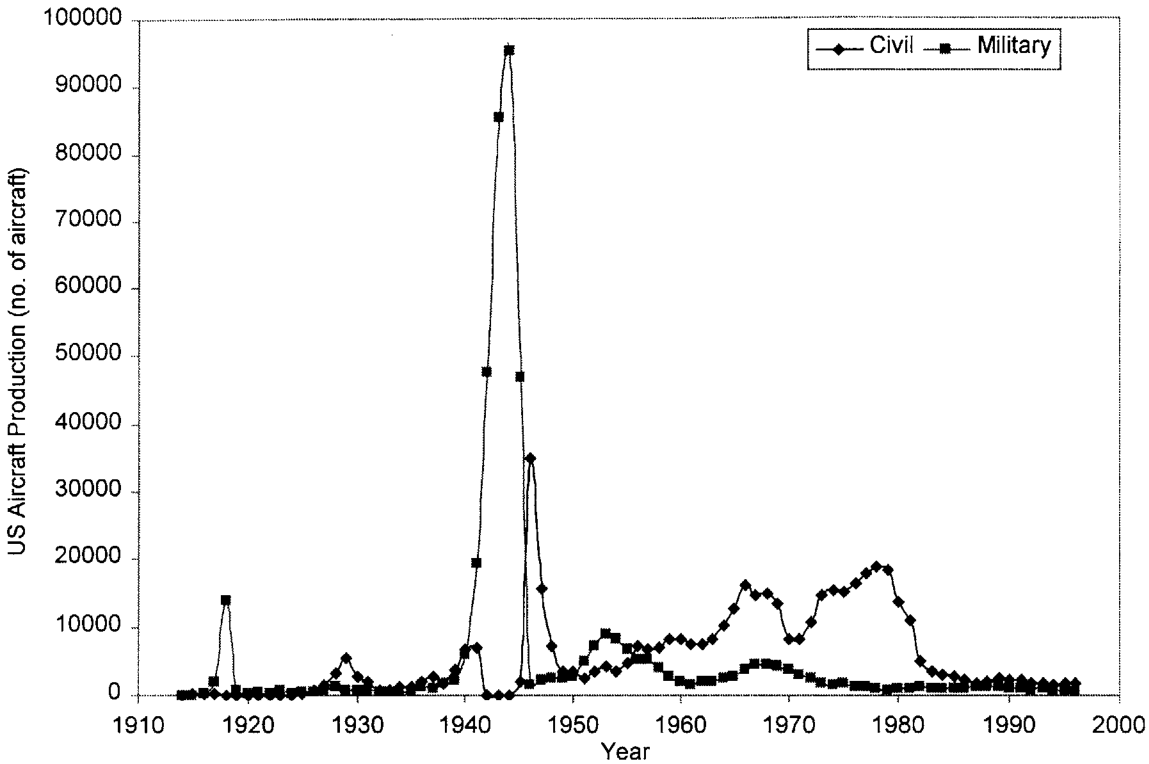

Figure 1: History of U.S. aircraft production[1]

Again, as military spending decreases as shown in Figure 2, efforts are now to make aircraft companies more efficient, so that they may survive this downturn, and maintain U.S. aircraft production capability.

[1] Data from Aerospace Facts and Figures 1970 and 1998, by Aerospace Industries Association of America, Inc. Table: U.S. Aircraft Production Calendar Years 1909 to Date (Number of Aircraft) and Tables: U.S. Aircraft Production – Civil and Military

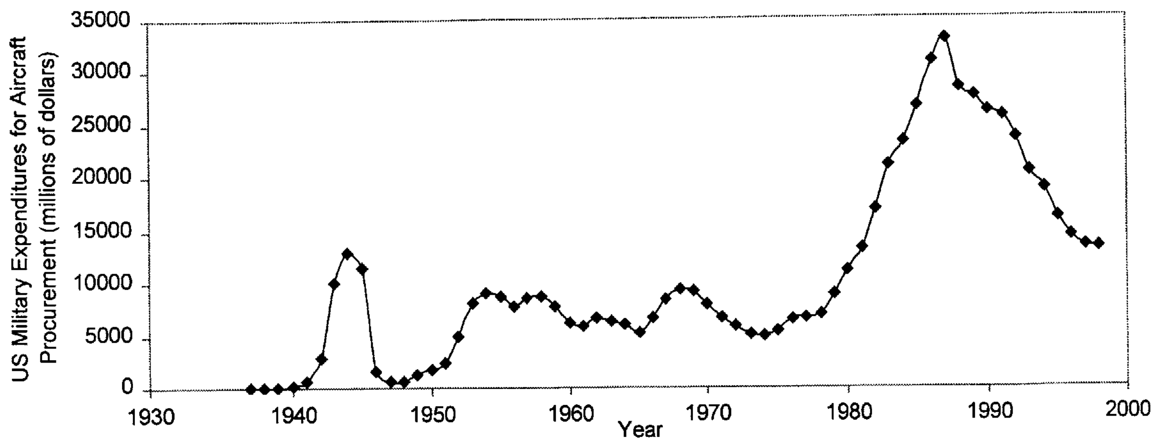

Figure 2: History of U.S. military aircraft procurement[2]

2.3 *LAI Research*

The design principles of the Toyota Production System transcend the automobile industry, with the lessons being applied in many different industries around the world – including the aircraft industry. Although *Lean Thinking* [Womack, 1996] alluded to an application of lean production in turbine blade grinding, the aircraft industry at that time had limited application of the TPS principles. The challenge to industry to apply these principles to their respective disciplines was met with the creation of the Lean Aircraft Initiative (now Aerospace) in 1993. This unique combination of government (US Air Force), Labor Unions, academia (MIT) and the private sector (defense aerospace firms and labor unions) intends to transform the industry.

LAI research has focused on identifying best practices from lean production that are applicable in the aircraft industry, as well as potential barriers to implementation. The research efforts are divided between five focus teams – Supplier Relations, Product Development, Policy and External Environment, Factory Operations, and Test and Space Operations.

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[2] Data from Aerospace Facts and Figures 1955, 1962, 1970 and 1998, by Aerospace Industries Association of America, Inc. Tables: Department of Defense Outlays for Aircraft Procurement

The framework used to organize all the research efforts within LAI is the Lean Enterprise Model (LEM) [LAI, 1996] which describe the lean principles and identify the practices. As an ongoing research effort, each of the concepts are continually supported through research by LAI. Selected findings from this thesis will also be incorporated into the LEM as well.

2.4 Production System Design Research

This thesis was written as a collaborative effort between LAI and the PSD laboratory. The PSD lab, headed by Prof. Cochran, approaches research in manufacturing from a systems approach as opposed to concentrating on improving specific operations. The mission is to conduct research in the development of a comprehensive approach for the design and implementation of lean production systems. Thus, the focus is on issues pertaining to design of systems with consideration of product design, machine design, human interface, performance measures, factory layout, and information systems. Through case studies in industry and numerous projects implementing lean production from the product development stage and redesigning mass production plants to cellular manufacturing, the PSD lab has encapsulated the knowledge of TPS from literature and experience in the form of the Production System Design Framework and decomposition [Cochran, 1999]. This work uses Axiomatic Design [Suh, 1990] to analyze how the methods of TPS integrate relationships between concepts and how they satisfy the overall business goals and strategy of the company to make a profit. Reynal [1998] provides examples in the automotive and aircraft industry to illustrate the applicability of the concepts from this design decomposition.

The advantage of using Axiomatic Design to describe TPS is that it provides a structured framework for analysis and further research [Cochran, 1994]. An introduction on Axiomatic design and its use in manufacturing systems is presented in chapter 4.

2.5 Contribution

The contribution of this thesis is the analysis of applying lean production to airframe assembly, an industry where interchangeable parts has not been totally achieved and where there is a high level of manually intensive work as opposed to autonomous stations. Use of the PSD decomposition is also applied in the analysis, which demonstrates its applicability to the aircraft industry. Axiomatic design is further used to determine the impact of procurement policies on production systems. In addition, building from the PSD decomposition is the development of an evaluation tool to aid manufacturers in analyzing their own production systems, identifying fundamental strategic changes for lean production as well as identifying areas to concentrate on to impact the production system design the most.

Chapter 3: Wing Assembly Case Study

To truly understand the nature of assembling aircraft, one of the most complex products in the world, a detailed view of the industry at many levels would be required. To do this the LAI Factory Operations group proposed a research effort titled "Design and Management of Complex Manufacturing Systems" using case studies to investigate the three main sectors – engines, airframe and electronics – of aircraft assembly. The original research plan is listed in Appendix A. This case study focuses on the airframe assembly sector following the work by Luis Ramirez in the engine sector [Ramirez, 1998].

3.1 Motivation

Each LAI consortium member wishes to learn how to convert a production system founded with a craft mentality in a lean production system. The researchers have been able to administer surveys and questionnaires but this has not provided the level of detail to reveal implementation issues. This project is designed to delve more deeply into member and non-member companies to understand how to design and manage lean airframe assembly systems.

3.2 Methodology

The approach used was field research at participating initiative member sites. Each site yielded a separate case study and multiple sites were investigated to generalize the overall study. The focus of this project is the study of the performance of the manufacturing system using the key metrics of planned assembly time, actual assembly time, reasons for delay and information about system characteristics. Through a disciplined approach to data collection the major contributors to perturbations in the manufacturing systems are explored for lessons on lean system design.

3.2.1 Selection of Sites

The airframe assembly sites were selected based on the following criteria:

- A group of products/companies that are representative of the defense and commercial aircraft companies in the US (focus on LAI consortium members)
- A group of products that are representative of the different types of aircraft in the defense and commercial sectors
- A group of products that have enough similarities to compare results
- Ability to visit sites over an extended period (typically 1 week) to collect data

The last criterion was undoubtedly the most restricting, especially since the investigator is a Canadian citizen. However, to address the preceding criteria, 5 sites were visited in total, 4 of which for an extended period of time (5 – 8 days) while one was visited for a shorter term (2 days). Companies of different sizes were represented as the study included one large aircraft company and one smaller one. The types of aircraft chosen were 4 military, and 1 commercial. Three were fighter aircraft, one was a large transport, and one was a smaller transport. To limit the scope of the study, only aircraft wings were studied. In addition, only wet wings (wings that are also fuel tanks) were chosen so that the complexity would be similar across the different products. Studying the assembly of wet wings to represent the airframe sector was agreed upon in consensus from the industry, military and academic members of the LAI factory Operations focus team.

Table 1 lists the different sites and some information about each one. Each product has been coded to ensure the security of any propriety information collected.

Table 1: Summary of Sites visited[3]

System Characteristics	A	B	C	D	E
Maturity of program	10-15 years	> 20 years	> 20 years	5-10 years	0-5 years
Production rate	4	3	4	0.67	0.58
Military/commercial	commercial	military	military	military	military

[3] Maturity of program determined by the number of years in production up to the date of the study (1997).

Although efforts were made to represent as much of the airframe sector as possible, the sites available did not include a high rate commercial assembler due to restricted access of the plants to the researchers. Unfortunately, this leaves a void in the study as high rate commercial aircraft may operate significantly different from those sites studied. To address this issue, references will be made to a thesis prepared by the Leaders for Manufacturing Program at MIT by Jackson Chao. His study entitled "Analysis of Variance Impact on Manufacturing Flow Time" will be used to include observations made on the Boeing 7A7 aircraft (particular model was not listed).

3.2.2 Site Visits

After each site was identified, it was visited initially for orientation and to familiarize the researchers with the people and data system at the company. The sites would then be followed with a longer visit of approximately 1-week to collect data. In some cases, there was also another visit to collect any missing data or information.

During the site visits, information was collected through a number of means. Conversations with the management, engineers, and crew yielded information using both informal and formal interviews. Information was also collected through the company's data system. There were also some efforts made to set up simple data collection procedures to collect data for a period of time.

Although an effort was made to collect the most accurate information, the process used has its drawbacks. The researchers were generally limited to the production areas of the companies. Questions better suited for other departments such as design, scheduling, human resources, etc. were answered with best efforts from the people available.

3.3 Observations

3.3.1 Assembly Process

The assembly process of each wing although unique has general characteristics, which are similar throughout the different products. Usually, the wing-box, which is the structural frame of the wing, is built up in a tool/jig with the spars and ribs. Leading and trailing edges are typically built separately and attached to the wing-box. Then, the skins are fitted and one side is closed off first. Before the other skin is installed, any internal hardware is first installed such as plumbing (for fuel), electronics, and hydraulic systems. The other skin of the wing is then installed.

The sub-assemblies described above are combined at different stages to build up the wing. Sub-assemblies are built in jigs (or tools) where parts can be precision located and held while fastening. Each of these stations is usually called a Work Center. Each Work Center has a designated area, crew, and tasks that are performed. Crew chiefs may lead one or more Work Centers.

Installation of parts requires a special procedure as airframe assembly is classified as type II assembly [as defined by Whitney, 1996] as parts do not locate themselves. (Type I assemblies are when the locating features are on the parts themselves.) During fabrication of a part, holes are drilled which are then used as reference features during assembly. The part is then located by aligning the reference holes with the jig/tool. Pilot holes are also drilled in fabrication that indicate the location of a fastener between two parts. After locating both parts, the pilot holes (on only one of the parts) are used as a guide to drill through both parts. This ensures alignment of the holes, which would not be achievable by drilling the holes separately in fabrication. Before fastening, deburring and sealing may also be required. Fasteners range from rivets to screws to interference fit fasteners. Because the hole pattern in each part is slightly different, the parts are not interchangeable – parts cannot be removed and fitted on another plane.

The most common material used is aluminum sheet metal and machined parts. Titanium, steel, and composites are also used in different amounts on different wings. The wing is complete when all the skins, panels and plumbing (fuel hoses) have been installed. The whole unit is then mated with the fuselage.

3.3.2 Scheduling

The Scheduling Process

The scheduling process begins with the number of aircraft to be produced per year. In the defense industry, this is determined by the contract and in the commercial industry, it is done by marketing forecasts and/or aircraft orders. The yearly production output is translated into a delivery schedule and using an MRP type of system, each major stage is scheduled by working backwards from these delivery dates (ramp, final assembly, wing, fuselage assembly, fabrication etc.). The times required for each stage are first estimations and may be modified in subsequent scheduling iterations. In each of these stages, the task is further broken down and scheduled into completion dates for each work center. In each work center, there are a number of tasks that must be completed and these are assigned to workers on a daily basis by industrial engineers or the crew chiefs.

Operating Schedules

After the schedule is in the system, it is the information system that coordinates production. It was observed however, at two sites that production was working to "recovery schedules". Due to a production system that has fallen behind schedule, in order to catch up, production had to be sped up in the short term in order to catch up. In these cases, the entire aircraft program would be on this recovery schedule.

At other sites where production was too far behind to catch up to the original plan, an entire rescheduling would be required. Rescheduling would mean that delivery dates would be changed in order to put production back on schedule.

Adherence to Schedule

One difference, between sites that was observed, was management's policies on adherence to the schedule. At one site, the wing would be delivered incomplete to fuselage mate (final assembly) in order to send it on time. This resulted in out of station work to be done in final assembly. At other sites, the wings would not be delivered until a greater degree of completion was achieved, but were often late.

3.3.3 Parts Supply

Parts arrive from different locations such as internal machine shops, external suppliers and other assembly areas producing subassemblies. Most parts destined for the assembly shop floor arrive at the plant and are placed into the parts crib. They arrive in various batch sizes depending on the part but there is a designed buffer time so that the first part of each batch will arrive 5-11 days before the actual need date (each company has its own schedule time buffer).

Parts used in assembly range from structural parts such as wing panels, spars, and ribs to brackets, rivets, hoses and other miscellaneous parts. As the work content is divided into different tasks or work packages, all of the sites have implemented delivery of parts in kits to varying degrees so that operators have most of the parts necessary for the job in one place. Large components which are too big for storage in the parts crib (spars, large skins) are kept in the assembly area next to their respective work centers. Small parts such as rivets and other fasteners are kept on the shop floor. In each area, there are small plastic chests, which hold many different fasteners and are replenished periodically by material handlers. At some sites, the small parts are being delivered to the floor in a "supermarket" style rack. Operators fill their chests from these racks and the material handlers fill the racks. Consumable supplies are also centrally stored and operators must walk to these centers to get sealant, drilled bits, brushes and other common supplies.

To prevent the worker from having to walk to get these supplies (sealer, cleaning solvents), one site has incorporated all the required parts and supplies in a kit. This observation was made in the fuselage assembly area but this technique is transportable throughout assembly.

Expediting System

For final assembly to proceed smoothly, it is critical that the parts required arrive on time to be put together. To prevent missing parts from causing shutdowns, each site has a methodology for forecasting part shortages so that the important or late items will be expedited. In general, forecasted late parts are generated from scanning a list of late parts projected by the MRP system. The person who actually performs this task varies between sites (either production control or crew chiefs).

While scanning these lists, the crew chiefs or production control considers what is actually in production, what will be needed soon and what parts are in the stock room. They generate a list of future short items. These lists are gathered from the different work centers and the most critical parts are expedited.

The expediting system may consist of regular meetings between a fabrication center and its customers (assemblers). The parts are ranked by how much impact they will have on assembly. This list of critical parts then supersedes the regular production schedule of fabrication. Now, the methodology described here is the "formal" method for dealing with part shortages. There is also an informal method where crew chiefs, the foreman or managers know which parts will be late and try to expedite them themselves through contacts at the fabrication centers.

3.3.4 Out of Station Work

Out-of-station work was observed at almost all of the sites to different degrees. Out of station work occurs when unfinished work planned at one station is left to be finished after moving it to the next station. When the work can be completed later, it is done so wherever the assembly is (out of its planned station). Common causes of out of station work are late parts, quality issues waiting for disposition, or when an assembly is falling behind schedule and the next station is ready for the assembly.

Out of station work allows the flow of assemblies to be on time so that downstream stations are not left idle. However, out of station work was reported to take more time for a number of reasons. Firstly, the assembly may be in a different orientation in a different station, which impacts access to the work area. Out of station work also means that work is done in different sequences which may not only impact variability but other installed components may hinder the out of station work.

As the operator is doing an installation at a different station, there may be more wasted time getting tools, parts or supplies which are not readily available in that station. Interfering with workers may also be a factor. Not only does the work take longer out of station but the operator is also not available for the regular scheduled work. Figure 3 illustrates the flow of parts, out of station work, and expedite signals.

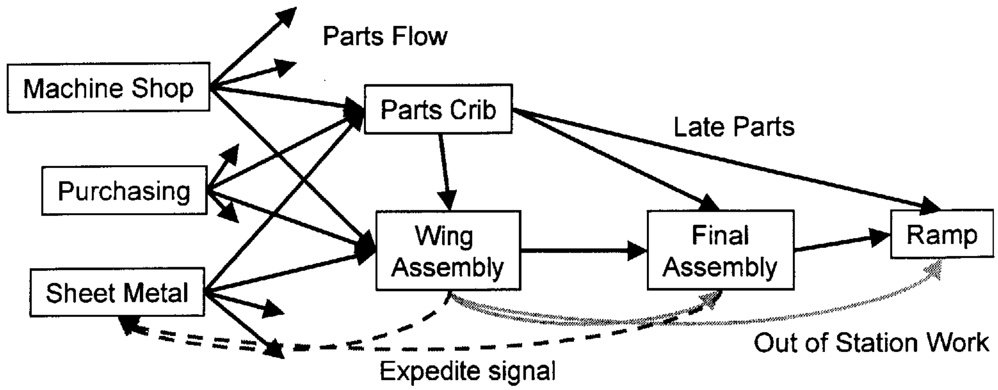

Figure 3: Flow of parts, out of station work and expedite signals

3.3.5 Operator Work

In airframe assembly, operators perform a wide range of tasks. These tasks include loading parts into jigs and precision locating parts together, drilling, reaming, installing and removing temporary fasteners, deburring, fastening, and sealing on many different parts and assembly stages. This description applies mainly to the sheet metal workers; other workers also do electrical, hydraulic and plumbing installations. If the throughput time of a work center were one week, an operator would have a week's worth of different tasks to do. The same task then would be performed only once a week assuming the same operator performs the same task from unit to unit (not always the case).

3.3.6 Inspection/Quality

At certain points in the assembly process, the work must be inspected. The inspector examines the work and checks it off in a column of the work instructions or makes an entry into the data system. When all the tasks for a workstation are complete, the assembly requires a full "shake-down", which is an overall inspection, before it can proceed to the next station.

At the sites studied, designated inspectors always did the inspection. When an assembly is ready for inspection, the worker signs an inspection log or enters a call into the data system and an inspector is signaled to check the work. No systematic method for determining the priority of jobs to be inspected when there is a queue was observed. At one site, the only parts that had priority were the sealing operations because the sealant should not be exposed to air and dust for too long. The work load on the inspectors varies greatly.

Non-Conformances

When a mistake is made during an assembly or when a quality issue is found by the inspector or the worker, it must be recorded and "reworked" to blueprint specifications. They are recorded as non-conformances and a non-conformance tag is written for each of them. An engineering disposition is written for it and the rework is done.

Corrective Action

Corrective action (CA) is the root cause detection and prevention method. Since the non-conformance tags represent the production problems, they are analyzed to see if the cause of any of these problems may be eliminated. If so, a Corrective Action will be written and implemented. The time it takes to respond to a CA ranges from a few days to months depending on the complexity of the problem (tooling changes take longer). It is interesting to note that the quality engineers assigned to this task have performance measures based on the number of CA's completed and the size of the paperwork queues.

Rework

The most common types of quality issues that require rework are mis-drilled holes, short edge distances, elongated holes, set marks, gaps or other mistakes.

Shimming/Trimming operations

In airframe assembly, parts must be fitted together with very precise tolerances. Because of the large size of the parts, their compliance, thermal expansion and tolerance stack-ups, the parts have to be jig located [Whitney, 1996] and in some areas, shimming or trimming operations are required. These operations remove interferences or fill gaps during assembly.

Many instances of these procedures were observed as part of the planned assembly process. However, there was one instance observed where gaps were appearing between ribs and the brackets and unplanned shimming was necessary. This unplanned work caused much delay, as shims had to be cut out of the correct thickness of shim stock and then sent out for paint. There was also much paperwork to accompany this process. This procedure had been institutionalized for a reported 7 years. This was a major source of delay in the system, which became accepted. After the initial visit, further investigation was taken and root of this problem was analyzed. It was found that one tool as well as one part was out of specification. However, these deviations did not account for the entire gap that was found so the shimming process continued. Although the shimming process continued, it was questionable whether it was really necessary. Standard sheet metal practice allows gaps that may be closed using finger pressure to be installed without shims. However, because the operators are used to shimming in this operation, they continued to do so. This is an example where root cause identification and the elimination would have great impact on the efficiency of the production system and should be carried out to completion.

3.4 Results of Data Collection

3.4.1 Throughput Time

In order to compare the throughput times of different wings, a common baseline at each site would be required. To do this, the throughput times of each wing were compared with their planned throughput time. This comparison assumes that the planned throughput times are consistent in terms of the complexity of the different products and do not have much variation in buffer times. To address this issue, the planned throughput times from site to site were compared to the number of unique part numbers of each wing.

To actually count the number of unique part numbers at each site was a difficult endeavor. The bills of materials (BOMs) are organized in a way that does not lend them to this type of analysis. Total part counts were difficult to obtain because parts such as fasteners do not have quantities called out in the BOMs.

To obtain a metric that described the number of parts that went into the wing, the number of BOM line items was counted. This figure will be close to the unique part count but will be a high estimate because multiple part types used in different parts of the assembly will be counted more than once. Since this was consistent at all the sites, this was used as a comparable metric to estimate complexity.

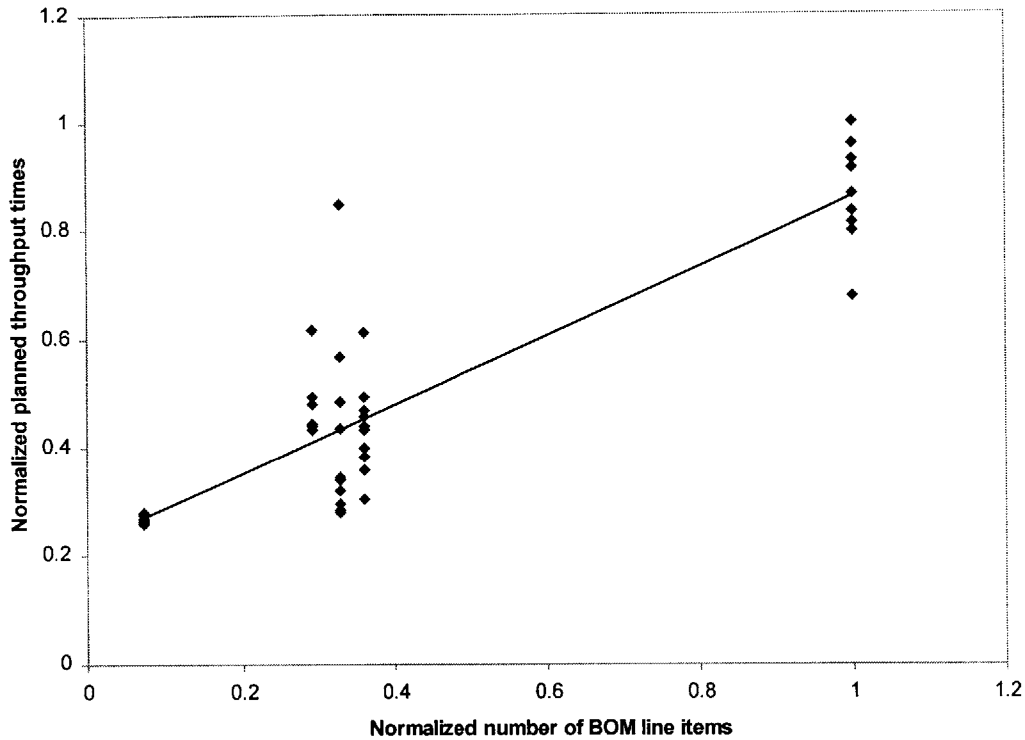

Figure 4: Planned throughput time vs. Number of BOM line items[4]

Figure 4 plots the planned throughput time of each wing with the number of BOM line items for that wing. Note that for each site, the number of BOM line items were the same while the planned throughput times varied. From wing to wing at a particular site, the number of different parts was assumed to be the same (there may have been slight differences). This assumption results in the five columns of data points observed, each column representing planned throughput time data from one site. The reasons for differences in planned throughput time at a site were due to efforts to decrease throughput time, and changes in production rate. The impact of production rate on throughput time may be shown using Little's law in Equation 1.

4 Number of BOM line items are divided by the maximum observed value to obtain normalized values. Planned throughput times are also divided by the maximum observed value to obtain normalized values.

$$\lambda = \frac{WIP}{Time_{Throughput}} \qquad \text{Equation 1}$$

where λ is the production rate. As production rate goes down and the level of work in process stays the same, throughput time increases. In practice, the number of workers is reduced which increases the throughput time at each station, which reduces production rate.

In order to test whether the planned throughput times scale with product complexity, providing a common baseline for comparison, the data in Figure 4 were analyzed. The Pearson's correlation coefficient for this set of data is $r = 0.87$ with 58 data points. To test if this relationship is statistically significant or not, the following hypothesis was tested[5]:

> *H_0: There is no statistically significant relationship between the throughput time and number of BOM line items for wing assemblies ($\rho = 0$)*
>
> *H_1: otherwise; there is a statistically significant relationship between the throughput time and number of BOM line items for wing assemblies ($\rho \neq 0$)*

The null hypothesis was rejected with a 95% confidence interval with a student's two-tailed t-test. This relationship suggests that the planning methods of each company are relatively consistent so that complex wings have longer planned throughput times. With this consistency, the performance of throughput times at each site may be compared with their own planned times and the ratios of planned/actual throughput times may be compared between different sites.

To compare the performance of adhering to the planned throughput time, the ratio of actual/planned throughput (build time) is plotted in Figure 5. Here, the averages as well as the longest and shortest times are shown. If a manufacturer consistently met their throughput time targets, the ratio would be 1, as represented by the dashed line. The sites have been ordered in ascending complexity (no. of BOM line items).

[5] The hypothesis testing equations used are presented in Appendix B

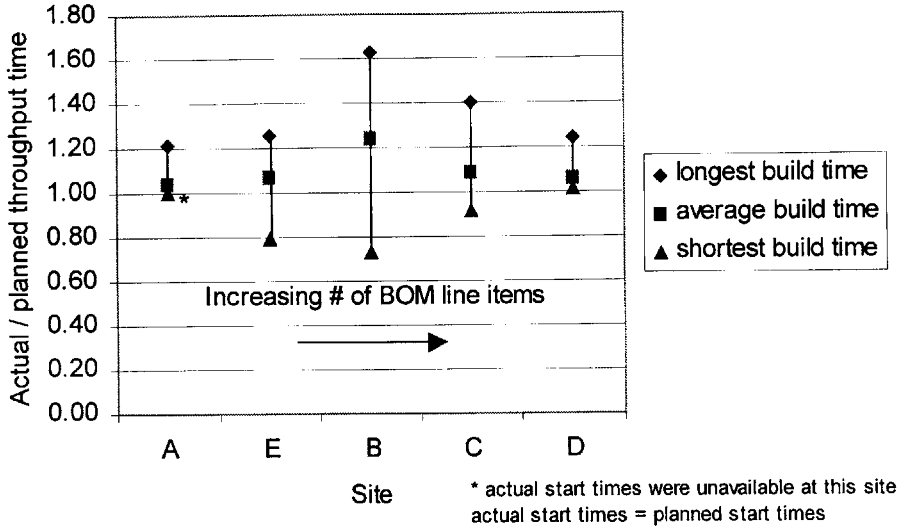

Figure 5: Normalized build-times at wing assembly sites

This graph (Figure 5) shows that on average, for each manufacturer, it takes slightly longer to build a wing than planned. However, at some sites there were units completed faster than planned by 20 percent and slower by up to 60 percent.

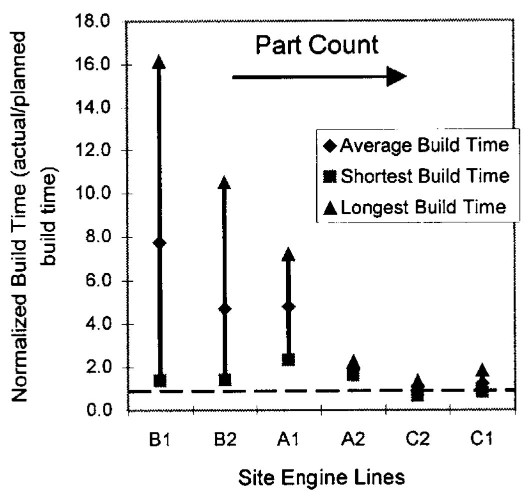

Figure 6: Normalized build-times at engine assembly sites [Ramirez, 1998]

In comparison with the study on the engine sector [Ramirez, 1998], these ratios are quite minor. Figure 6 shows the results from the engine sector study by the LAI factory operations team. With this analysis, it was clear that site C was outperforming its competitors by a great deal. Not only was the average ratio of average/planned throughput time drastically lower, the variability was also much less. Using this contrast, the system differences were compared to illustrate the impact of their implementation. The story communicated by this analysis motivated the same methodology in the airframe sector. However, the results were not nearly as conclusive. If data from the airframe sector were plotted next to the engine results, they would all be similar to the results of engine A2 from Figure 6. There are however a number of factors besides performance that explain why this is the case.

First of all, the low actual/planned ratios in wing assembly may be due to the way it was measured. As opposed to engine assembly where the engine was complete when delivered, it was not so with the wings. Throughput time is measured from when the first work package begins for a particular unit to the time the wing is delivered to final assembly. The interesting part is that it is not always complete when delivered. At some sites, after the wing is sent to final assembly, workers from the wing area are sent down with it to complete unfinished work. In order to stay on schedule, the wings are delivered incomplete but ready to join with the fuselage. With this in mind, the measure of throughput time loses some of its meaning. Perhaps throughput time should extend until the last item is complete but its comparative value is compromised even further (could not determine this time from data system). Secondly, in order to meet delivery dates the manufacturing lead times (planned throughput times) may be established to allow for the variability and uncertainty in production. The larger the amount of uncertainty, the greater the lead time. Thirdly, the time scales are longer so although the ratios are low; the actual number of days difference between actual and planned throughput time ranged from 10 days less to 45 days more.

The results of comparing throughput time are not as telling as hoped. Although there is some difference in the averages between the different sites, they are not statistically significant. This means that the sites themselves are not performing differently, not enough samples were taken, or this metric does not show differences in performance.

The sample size for this data ranged between 7 to 12 units, all based on data from 1997 records.

3.4.2 Schedule Performance

Another measure that may distinguish lean systems is performance to schedule. This measure however is even harder to compare between the sites. At a number of the sites, the assembly was operating on a recovery schedule (to catch up) and in some cases, if they fall behind enough, they reschedule to start on track again. Also, since wing assembly feeds final assembly, if final assembly is behind schedule, wing assembly will slow down as well. Thus, taking measurements on schedule performance does not reflect how well a system is performing, rather it reflects how well the schedule is adjusted to accommodate the production output. Perhaps measuring schedule performance in relationship to original contract dates would have been consistent enough. There was however, enough ambiguity about the relationships between shop floor schedules and contract agreements that schedule performance was not used as a metric in this study.

3.4.3 Quality

Quality cost is often measured as "non-conformance cost". Non-conformance costs are the labor and overhead applied to repair or rework quality issues. Non-conformance costs in comparison with total labor costs were estimated to range from 15 to 36% among the wing assembly sites. Comparisons are not made with these figures because they were calculated differently at each site (included different costs). However, it does illustrate the high impact of quality on cost in the airframe sector.

The amount of effort for repair and rework was also recorded. Figure 7 shows the percentage of labor hours spent on repair and rework with respect to the total hours to build the wing. With up to 17% of total labor hours addressing quality issues, it depicts an industry where the amount of rework performed is high. The philosophy of "first-time right" has not been totally achieved yet in this industry. As this presents an opportunity for improvement, further discussion on the factors which impact quality will follow. Site A had the lowest percentage of rework and repair, which may be because it is a commercial wing with lower performance and tolerance specifications.

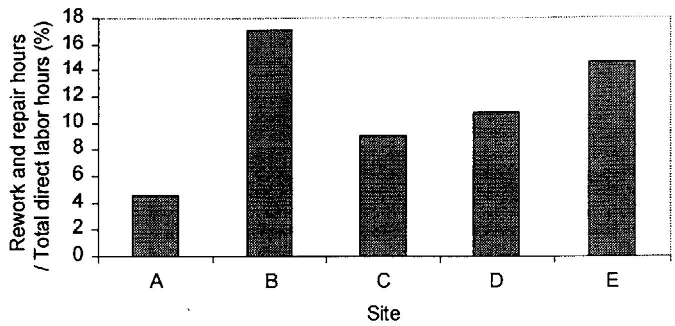

Figure 7: Rework and repair hours / Total direct labor hours at each site

To assess the impact of quality problems on cost, the actual labor hours to build each wing are plotted against labor hours for rework and repair in Figure 8 with data from site B. Each point in the graph represents one wing and the amount of rework and repair hours and total labor hours required to build it. The correlation values for this set of data is r = 0.87. To test the significance of this correlation the following hypothesis was tested:

> H_0: *There is no statistically significant relationship between actual labor hours to build each wing and the labor hours for non-conformances for each wing assemblies ($\rho = 0$)*
>
> H_1: *otherwise; there is a statistically significant relationship between the direct labor cost per unit and the non-conformance cost for each wing assemblies ($\rho \neq 0$)*

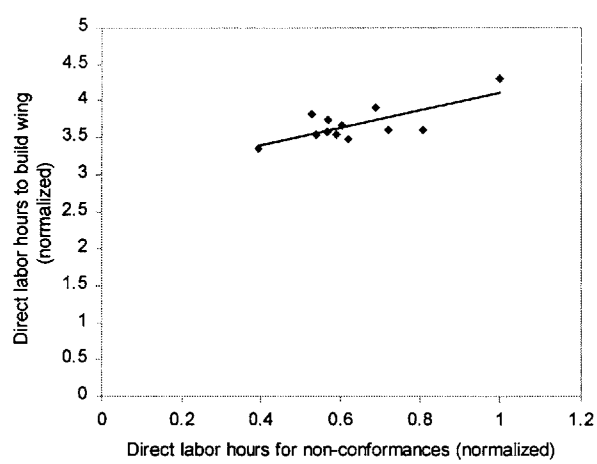

Figure 8: Impact of quality on labor cost[6]

[6] In this graph, both axes have been normalized by dividing by the highest value of labor hours for non-conformances. Because both axes have been divided by the same value, the slope is not distorted.

The null hypothesis was rejected with a 95% confidence interval so there is a statistical significance in the correlation between non-conformance cost and direct labor cost per unit. This result makes sense because units that require more rework would naturally incur greater labor costs. The slope is approximately 1.2 and suggests that for every hour of repair and rework that is performed, direct labor hours increases by 1.2 hours.

A similar comparison was made with throughput time at this site. Throughput time per unit is plotted against non-conformance cost in Figure 9. The correlation values for this set of data is r = 0.58. To test the significance of this correlation the following hypothesis was tested:

> H_0: *There is no statistically significant relationship between throughput time per unit and the non-conformance cost for each wing assemblies ($\rho = 0$)*
>
> H_1: *otherwise; there is a statistically significant relationship between throughput time per unit and the non-conformance cost for each wing assemblies ($\rho \neq 0$)*

The null hypothesis was rejected with a 95% confidence interval showing statistical significance in the correlation between throughput time and non-conformance. This result shows that rework causes delays that impact throughput time. The line of best fit had a slope showing an increase in throughput time by 5% for every 100 hours of rework/repair.

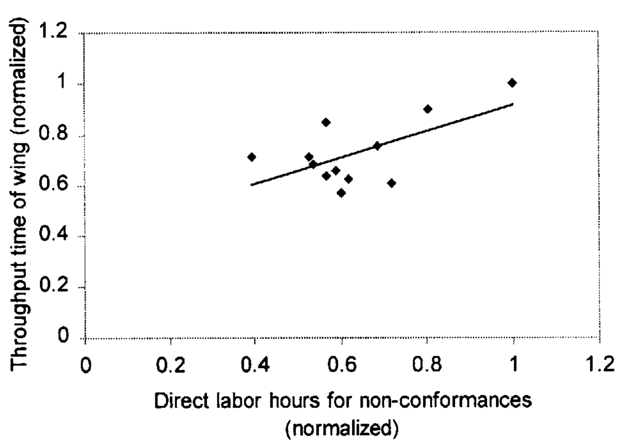

Figure 9: Impact of quality on throughput time[7]

[7] Both axes have been normalized by dividing by their respective maximum observed values.

With an r value of 0.58, the relationship is rather weak between quality and throughput time but can be explained because there were many other factors reported that impact throughput time (parts, people, tool availability). The slope of this graph from the original data (before normalizing) showed an increase in throughput time by 5% for every 100 hours of rework.

The high impact of quality problems on labor cost also exists in high-rate commercial aircraft production. Chao and Graves [1998] analyzed the impact of system variances on direct labor hours in the assembly of the commercial aircraft. They also reported that "defects accounted for a significant portion of direct manufacturing labor input." Unfortunately, they did not present the actual proportions that would have allowed a direct comparison.

3.4.4 Overtime

The amount of overtime worked by the operators is presented as a percentage of the total amount of labor hours over one year for most sites (1997) and is presented in Figure 10.

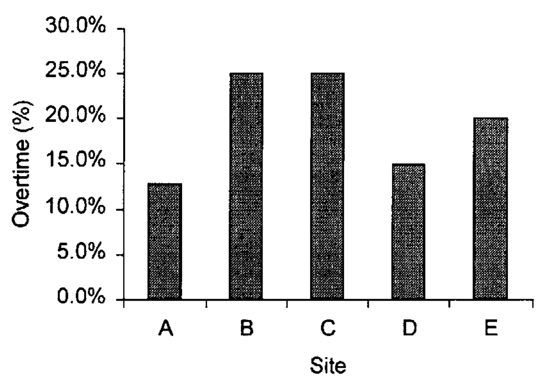

Figure 10: Overtime worked at each site

3.4.5 Labor Cost

The metric used most for assessing cost in assembly is the number of direct labor hours spent on building each unit. Every time an operator completes a task, they "clock in" entering the amount of time, the type of work and the unit number (and in some cases the task number).

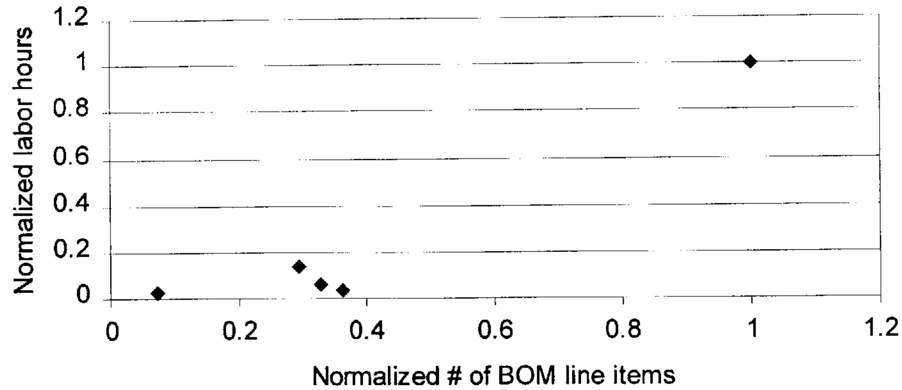

Figure 11: Labor hours vs. BOM line items at the different sites[8]

To compare the cost in labor hours required to build each type of wing, the labor hours were plotted vs. the number of BOM line items of that wing in Figure 11. It is apparent that labor cost does not scale as nicely with complexity as throughput time does. This is most likely due to the different levels of maturity of each program. Chao and Graves cite two variables which impact labor cost: complexity of the assembly and the number of times the unit has been put together. Among the different sites, the number of units produced ranges from under a dozen to over a thousand. To address this issue, a learning curve was used to estimate the number of labor hours for the first unit. Although some of the improvement may be attributable to operator's learning of the tasks, another portion is from making improvements or cost savings projects to make the assembly easier to build. This may be viewed as the learning curve of the assembly system [Snobby, 1926]. Figure 12 shows the curve which describes the learning observed in the assembly, plotted from the simple equation established by Wright [1936] in the aircraft industry,

$$t_n = t_1 n^{-b} \qquad \text{Equation 2}$$

where t_n is the time to build the *n*th unit, t_1 is the time for the first repetition, *n* is the unit number and *b* is the learning rate. The learning rate b of 0.38 was determined by fitting the curve to two of the sites where the initial number of labor hours was known.

[8] were again normalized by dividing the data by the maximum observed value to obtain a ratio

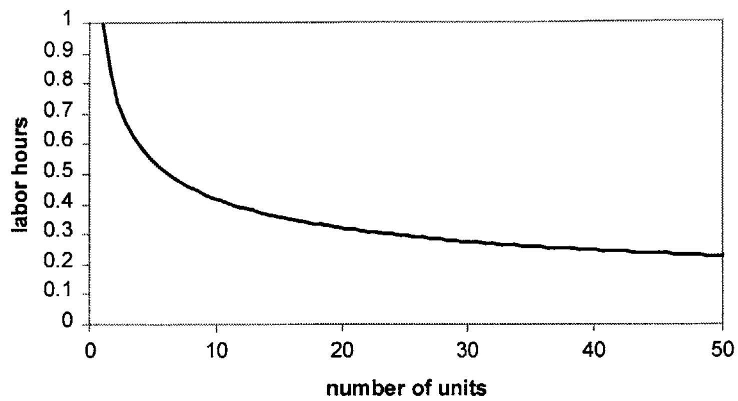

Figure 12: Learning curve used to estimate number of labor hours of first unit

Using the learning curve in Figure 12, estimations of the labor hours for the first unit at each site were determined. However, this comparison is not further analyzed because the analysis was extremely sensitive to the learning rate used.

3.4.6 Out of Station Work

To assess the impact of out of station work on direct labor cost, data was used from one site where the number of out of station work hours done in final assembly was available. The relationship of out of station work with total labor hours is graphed in Figure 13. The correlation between the number of out of station hours and total labor hours is $r = 0.92$ with a slope of 0.8 (for every hour of out of station work, the total number of labor hours increased by 0.8). This slope suggests that an hour of work requires 1.8 hours to complete out of station. To test the significance of this relationship, the following hypothesis was tested:

> *H_0: There is no statistically significant relationship between total labor hours and the amount of out of station work on a wing assembly ($\rho = 0$)*
>
> *H_1: otherwise; there is a statistically significant relationship between total labor hours and the amount of out of station work on a wing assembly ($\rho \neq 0$)*

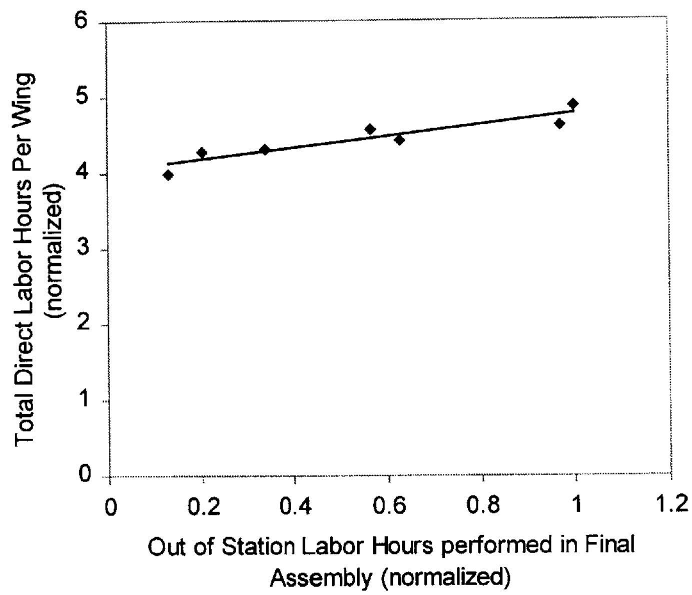

Figure 13: Labor hours vs. Out of station work[9]

The null hypothesis was rejected with a 95% confidence interval with a student's two-tailed t-test. Although it cannot be determined that the relation between Out of Station work and labor hours is causal, it may be assumed that if the reasons for Out of Station Work is decreased, labor hours for each wing will decrease as well.

This analysis does not show if the task takes longer to do out of station than in station. To determine this, the work content done in final assembly would have to be known with the corresponding amount of in station work to complete it. This type of analysis was attempted at one site, but the out of station work hours included other tasks, which prevented a direct comparison.

The amount of out of station work at different sites depends largely on the management policy. At one site, delivery of the wing on time was adhered to but the wing was often delivered incomplete. Other sites did not deliver the wing incomplete but were often late. Thus, these production systems are trading-off labor cost for on-time delivery to final assembly.

[9] Both axes are normalized by dividing the values by a constant value so that the slope is not distorted.

3.4.7 Delays

The Toyota Production System drastically reduced throughput time by eliminating delays due to large batch sizes, large run sizes, and excessive amounts of inventory. In airframe assembly, single piece flow is used, which eliminates lot delay and run size delay. One reason for long throughput times in airframe assembly is due to a more basic cause, high variation in assembly. Because of this variation in build time, buffer time is added into each workstation, which increases throughput time. To characterize the sources of time variation, the delays in aircraft assembly are analyzed. For the purposes of this analysis, a delay occurs when work cannot be performed when it is supposed to be done.

There was an effort to determine the reasons for, and impact of delays to wing assembly. A delay was defined as when work could not be done when it was supposed to be. There was no formal recording system for this type of data, so informal interviews were used at first to determine the types of delays that were common. This was followed by a more detailed interview (listed in Appendix B). After the first round of visits, some of the sites actually began to collect delay information data. Table 2 summarizes the data collected and interview data was used where necessary.

Table 2: Reasons for Delay

Delay Categories	A*	B	C*	D**	E
Work planning, out of station/sequence	10%		19 %	9 %	24 %
Quality (rework, repair, inspection)	44 %	13 %	33 %	11 %	34 %
Parts bad/unavailable	21 %	2 %	17 %	41 %	23 %
Tooling/machines down or unavailable	3 %	56 %	7 %	30 %	19 %
People unavailable	22 %	29 %	24 %	9 %	

Percentages represent breakdown of time delay (each column totals to 100%)
* Delay data collected by interview
** Percentages reflect event count instead of time delay (does not reflect impact)
Blank entries represent no data in that category collected by the site (may still be a source of delay)

It was found that the distribution of the delays was different in nature from site to site. In the engine sector, parts availability was the most critical source of delay. In aircraft assembly, quality problems on average were the greatest sources of delay (which is consistent with the rework data presented in Figure 7). At the two newer sites, (D and E), part shortages were more of a problem. At sites where large automated drilling machines were used, more delays were attributed to machines being down. People availability was a large source of delay at 3 sites but may have been a seasonal effect as the data was collected in the summer months when vacations are usually taken. At site E, the data collection system did not capture people availability.

Chao and Graves identify part shortages and rework as main variances which impact direct labor hours for the commercial aircraft studied. Although their study focuses on reducing flow time, they were unable to relate flow time variation to system variances. Relating the delays to throughput time was not achieved in this study as well. Only the relative time impact of each delay category could be assessed.

3.5 Summary

In comparing the wing assembly sites from the data collected, little insight into differences in the system characteristics or performances was gained, due to the variation in product design and program maturity. However, the observations and data were used to characterize the industry and identify opportunities for improvement.

Non-conformance costs (labor plus overhead) were large (15-35%) compared with the total labor cost of assembling a wing. In proportion, 4 – 17 % of total labor hours were spent on rework and repair. Rework and repair hours also showed a correlation with total labor hours and throughput time. Data from one site showed that for every hour of rework/repair performed, the total direct labor hours increased by 1.2 hours. The throughput time also increased by 5% for every 100 hours of rework.

The production disruptions observed and reported were due to quality, part shortages, waiting for inspection, waiting for engineering, design changes, people availability and machine/tool availability. The relative frequency and impact of each type of disruption varied among the different sites but quality (non-conformances) was the most consistently reported disruption.

Although these production disruptions occurred frequently, their impact was hidden, as the planning is conservative enough for these disruptions to occur without greatly impacting the schedule. In most cases overtime – high levels observed (13 – 25%) – was also used to alleviate the impact of production disruptions.

Studying actual/planned throughput times in airframe assembly did not yield a significant contrast. All sites were able to meet their planned throughput time to a similar degree because the manufacturing lead-times were set to allow delivery on time with the expected amount of production disruptions. This made actual/planned throughput time a poor comparison metric in this case.

The impact of out of station work was analyzed at one site. For every hour of out of station work performed, the total direct labor hours for the corresponding wing increased by 0.8 hours. This result suggests that an hour of work in-station requires 1.8 hours to complete out of station.

Chapter 4: Introduction to PSD Analysis

Although much has been written about the Toyota Production System, it's application is not trivial as many companies have experienced. Many of the observations and concepts have been presented, but there still lacks a structured framework to describe TPS. In this chapter, axiomatic design will be introduced as the methodology for the PSD decomposition that describes a generalized lean manufacturing system. Based on this decomposition, a production system design evaluation tool is developed in chapter 8 that assesses the attributes of a production system, providing an understanding of the design of the existing system as well as what would be necessary to convert to a lean system.

4.1 Axiomatic design[10]

In designing a complex manufacturing system, a well-defined methodology should be used. Axiomatic Design [Suh, 1990] is used because it provides a foundation for setting requirements, establishing potential design solutions and selecting the most favorable ones through defined axioms and theorems.

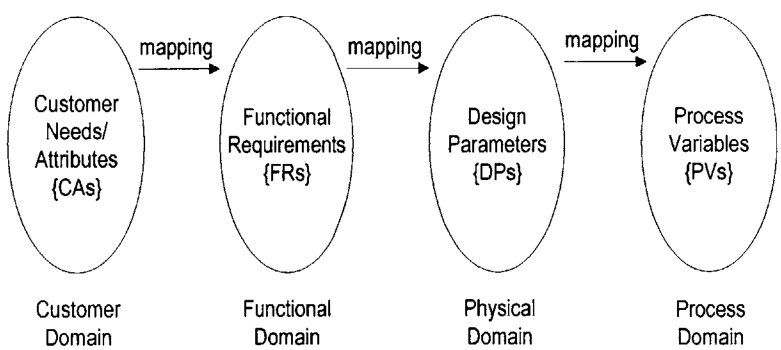

Figure 14: The 4 domains in axiomatic design

The basic process in Axiomatic Design is the mapping between the four domains, the customer needs, the functional requirements, the design parameters and the process variables

[10] This brief introduction on Axiomatic design is based on the *Principles of Design* by Nam P. Suh

as shown in Figure 14. Between each of the domains is a mapping process where "what is to be achieved" is on the left and "how to achieve it" is on the right. In the design of a manufacturing system, after identifying the customer needs, mapping proceeds between functional and physical domains. FRs represent what the business goals, or objectives of the system are and the DPs describe how they are physical achieved. DPs often describe attributes of machine design, information systems, and operator work design in manufacturing.

Axiomatic design is based on the following two axioms:

Axiom 1: The Independence Axiom

Maintain the independence of the functional requirements (FRs)

Axiom 2: The Information Axiom

Minimize the information content of the design

The independence axiom states that the FRs should be defined as the fewest number of independent requirements that describe the goals of the design. These FRs should also be satisfied by DPs that do not impact other FRs. As an example, consider two FRs satisfied by two DPs. The relation between the FRs and DPs may be described by a design matrix as shown in Figure 15. The design matrices indicates which DPs affect an FR. In an uncoupled design (identity matrix), one DP only affects its corresponding FR. In a decoupled design, (lower triangular matrix) DP2 affects both FRs but DP1 only affects FR1. This is a path dependent design because to satisfy the specified FRs, DP2 must be adjusted so that FR2 is achieved, then DP1 may be adjusted to satisfy FR1 as shown in the diagram. In a coupled design, each DP affects each FR, which makes it difficult to control. Coupled designs often require iterative methods or optimization algorithms to achieve the objectives. To follow the independence axiom, the FRs should be satisfied independently as in uncoupled designs where possible, and decoupled designs otherwise.

	uncoupled	decoupled	coupled
Design Equation	$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$	$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$	$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$

Graphical Representation

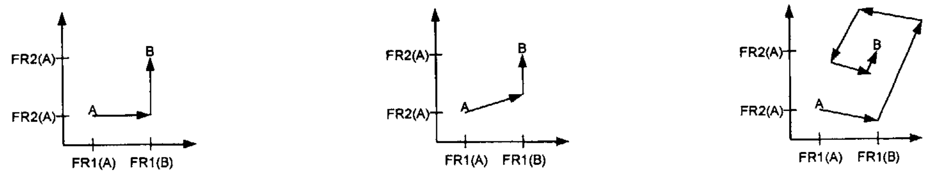

Figure 15: Types of design (impact of design matrices)

The information axiom is further explained in chapter 8 with how it impacts the evaluation of a production system.

4.2 PSD decomposition[11]

To provide an example of how axiomatic design is applied, top three levels of the PSD decomposition are presented here – an application of the axiomatic design methodology in formulating the design of a generalized manufacturing system [Suh et al., 1998]. The entire decomposition is listed in Appendix D as a reference.

4.2.1 Decomposition of Top Three Levels

To begin with a top level FR, the overall purpose of the manufacturing system must be determined. As stated in *The Goal* [Goldratt, 1984], the ultimate goal is to make a profit, leading to *FR1: Maximize return on investment.* The process of design now calls for the selection of a DP to satisfy this FR. Other possibilities may be to make investments but the focus of this study is in manufacturing so the *DP1: Manufacturing system design* is selected. Further decomposition continues by mapping from the DP back to the FR domain. Since the DP does not give enough detail to implement the design, further requirements are developed.

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[11] This design decomposition is based on the work of Prof. Cochran and Prof. Lima. The development of version 5.0 of this decomposition involved many of the students of the PSD lab, Jorge Arinez, Staffan Bröte, Micah Collins, Daniel Dobbs, Jim Duda, Yong Suk Kim, Kristina Kuest, Jochen Linck, Jose Castaneda-Vega and Andrew Wang. Much appreciation goes to this team for the many long discussions allowing the sharing of ideas and experiences.

The next set of FRs represent the elements of the ROI equation of sales revenue, production cost and production investment.

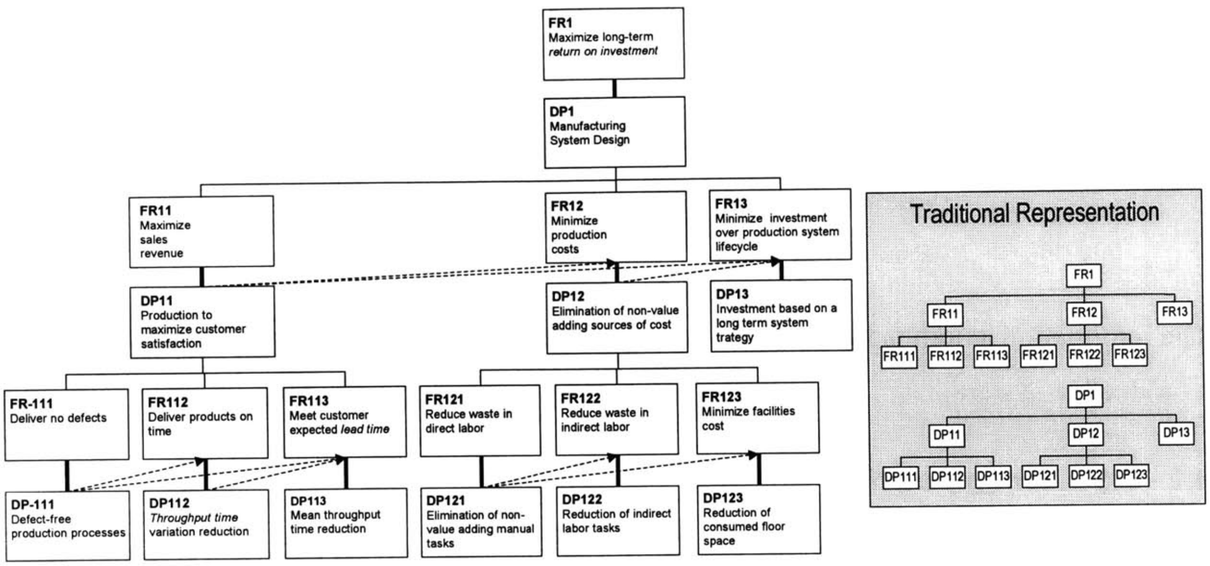

Figure 16: Top three levels of PSD decomposition

Figure 16 shows the top 3 levels of decomposition in a format that shows the flow from FR to DP to further decomposed FRs. It is presented in this format to depict the flow of decomposition and the impact of DPs on other FRs (dashed lines). The traditional method of representing the decomposition keeping the functional and physical domains separated is also shown.

To increase sales revenue, in a market where the focus is on satisfying the customer not only with the merits of the product but also with how the product is produced and delivered, *DP11: Production to maximize customer satisfaction* is used. This DP replaces that of maximizing production, used in the mass production era when all products that could be made could be sold. This DP is further decomposed into the requirements of delivering no defects, delivering products on time, and reducing the customer lead-time. In satisfying these FRs, new approaches are taken again. Instead of producing defects and using end-of-line inspection to detect them, production without defects is incorporated. To deliver on-time and within the customer expected lead time, instead of amassing large levels of inventory to deliver from, the variability in and mean throughput time are reduced. These DPs express the TPS methods of eliminating waste within the manufacturing system. Note that production to maximize customer satisfaction has impact on the FRs of production cost and investment, because waste eliminated in delivering products to customers decreases production cost. As well, many of the requirements for the machines are also determined in the branch that impacts the production investment. In systems where machine investments have very long cycle times, they may be specified without considering the overall design of the system. This methodology considers investment last so that machines may be acquired which satisfy all the requirements of the system decreasing the long-term investment cost.

To satisfy *FR12: Minimize production costs, DP12: Elimination of non-value adding sources of cost* is selected. This DP is further decomposed into direct labor, indirect labor and facilities cost. Again the decoupling of the design matrix indicates that DP12 impacts FR13: Minimize production investment. This relationship again stresses the fact that decisions about production investment are dependent not only on the process but how they are operated; investment with a systems thinking approach.

Traditionally, the *FR13: Minimize production investment* is satisfied by reducing the number of machines. Acquiring machines in this manner limited the way that they could be operated. In this design decomposition, it is recognized that Toyota was able to acquire machines to allow linked cell production flowing to customer takt time, designed and arranged in a manner to allow efficient use of operators handling many machines. This is expressed through the design matrix and *DP13: Investment based on a long-term strategy* implies that to minimize production investment, the long term system cost should be considered as opposed to the initial investment. This is not decomposed further because these decisions will be highly dependent on the strategy of how much volume and product flexibility are required of the system.

Applicability to Aircraft Assembly

Although the PSD decomposition principles were derived from the automotive industry, subsequent revisions have considered the generalization of the model across different industries. Regardless of industry, manufacturers want to satisfy the top level FR to maximize return on investment. Even if company strategies are different (such as selling under cost to capture market share) the ideas of maximizing customer satisfaction, minimizing production cost and investment is still applicable.

In the defense aircraft industry, the ultimate goal may be to provide the maximum amount of defensive value with the available resources. As the military attempts to satisfy this requirement, manufacturers must show ability to deliver quality products on time and within the expected time while minimizing production cost and investment to win contracts and make a profit. Factors that drive manufacturers away from this design at a high level are discussed in Chapter 7, taking into consideration demands from the military and the procurement policies.

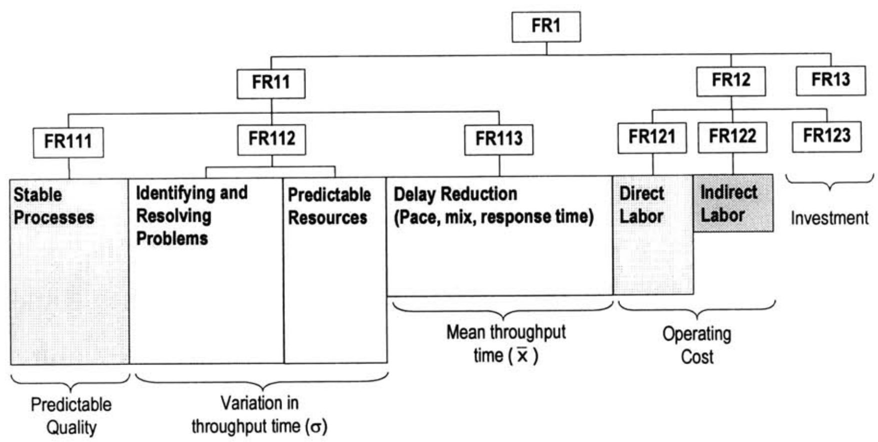

Figure 17: Further PSD decomposition topics

After the first 3 levels, the decomposition can be described further in the 5 categories as shown in Figure 17. These topics will be described further in concept with their application to the aircraft industry as they are applied in a revisit of the wing assembly case study in the next chapter.

Chapter 5: PSD Analysis of Wing Study

Using the decomposition introduced in the previous chapter, the wing assembly case study is now revisited using this decomposition as a structured framework for analysis of how the systems have been designed with respect to that of a lean production system design. Comparisons will also be made in how the concepts differ in their application to the aircraft and automotive industries.

5.1 Quality

In order to deliver high quality products, deliver products on time and reduce throughput time the production system must be capable of producing without defects. This is why a characteristic of lean production and the Toyota Production System is the unending drive towards perfect quality. At Toyota, in the spirit of eliminating waste, great efforts are made to prevent the production of defects, catching mistakes as soon as they occur and solving root causes of quality problems immediately so that they are not repeated.

In airframe assembly, perfect quality has an entirely different connotation. These are products where a quality issue, no matter how minor, may cause a malfunction immediately jeopardizing many lives or that of a pilot or a strategic mission. In one sense, these aircraft are among the highest quality products in the world. To accomplish this, 100% inspection is used and quality issues are usually reworked. Although inspection is usually done by inspectors, there is a trend in the industry to increase the amount of responsibility and self-inspection by the workers themselves. Although total elimination of second party inspection may not have been implemented, decreasing the amount of tasks requiring additional inspection is possible.

A number of factors are important in distinguishing between quality achievements attainable in the automotive and aircraft industries such as process capability, volume and interchangeable parts. Regardless of overall levels of quality achievable, both in the aircraft and automotive industries, quality problems must not be left to the end of the line or process for inspection and rework. Problem must be identified immediately and a procedure to eliminate their reoccurrence must be initiated. Figure 18 depicts the decomposition of the quality branch showing that to get to defect-free production, the process must first be stabilized to determine the process capability and then improved upon.

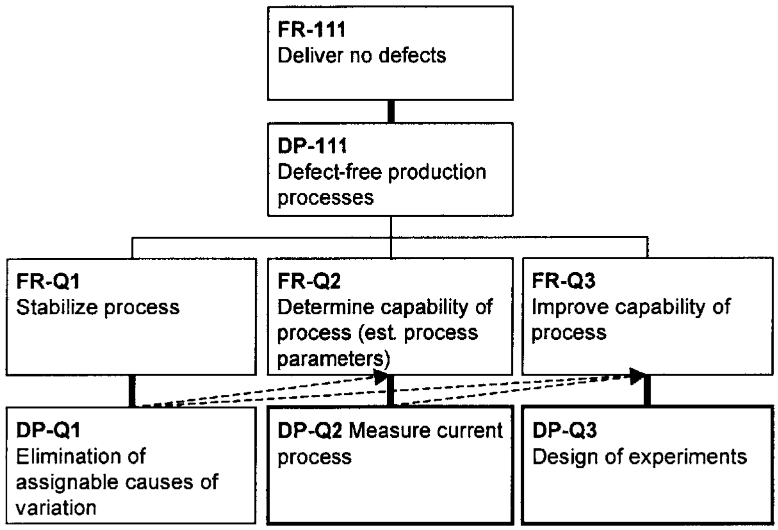

Figure 18: Decomposition of *FR-111: Deliver no defects*

5.1.1 Stable Processes

To stabilize the process, assignable causes of variation from equipment, people, methods and material must be removed as shown in Figure 19. It must be noted that the issue of design and process capability plays an important role here. The PSD decomposition assumes that the design allows the parts to be put together the same way each time (further research on incorporating product design into this model is underway).

In airframe assembly, this has not been achieved as the high dimensional variation of parts with respect to the tolerances require that operators fit the parts together slightly different each time. This has a strong impact on standardizing the work and stabilizing the processing times. To address this, the design must allow the parts to be assembled the same way each time. Along with more emphasis on design for manufacturing and assembly, datum flow chain analysis [Whitney, 1996] may provide methods to better define how parts are assembled.

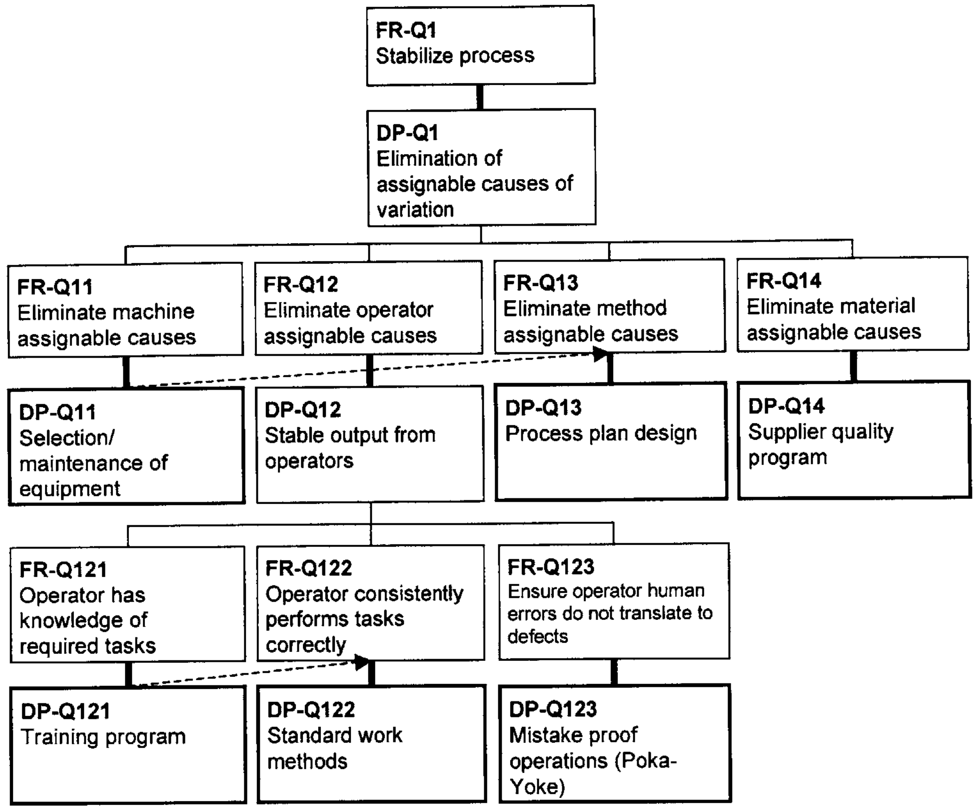

Figure 19: Decomposition of *FR-Q1: Stabilize process*

5.1.2 Equipment

The equipment in assembly includes the tools and jigs, hand tools such as drills and grinders and automated machines such as the automated drilling machines. At the mature sites, the tooling and jigs were observed to require more maintenance. Tooling were not regularly maintained and problems were reported to take up to months to be addressed. The precision hand tools at these sites were kept in random bins, stacked on top of each other in disarray. Implementations to improve the equipment upkeep was observed as standard tool kits were designed so that each tool has a designated place and is kept in better condition. The automated drilling machines were capable of drilling hundreds of holes to precise tolerances. However, when quality issues arose, it usually meant that mistakes were multiplied. Since the main problem with these machines was their downtime, they are further discussed under throughput time variation.

5.1.3 Operators

In order to ensure stable output from operators, they require the knowledge of the tasks, a consistent method to perform tasks and a way to decouple human errors from the production of defects. These requirements are achieved through training, standard work methods, and mistake proofing operations.

In the aircraft industry, the level of standardization is limited because of the high dimensional variability of the parts that may require custom fitting each time. However, this makes training, instructions and knowledge retention more critical. As workers are faced with difficult assemblies, they gradually learn special methods to fit the parts together to allow the assembly to come together with the fewest problems. These methods, often called "tribal knowledge" on the shop floor, are valuable. If these methods may be instituted through the training and standard work methods, they will help to stabilize the process.

Training

In an industry with high amounts of skilled manual work, the ability to maintain and improve skills is critical to the company's success. One of the observations was that there was a great deal of change in the work force at the different sites. Reasons of this were mainly, changes in production rate, retirement and transferring to different departments. Production management often cited new workers as a source of quality issues or general reason for falling behind schedule. Along with standardizing the tasks and continually improving/updating the work instructions, the training program contributes to maintaining predictability in quality and time of the assembly process.

Shop floor workers are considered highly skilled technicians who have formal training in various types of work such as sheet metal work, sealing, riveting, drilling, hydraulics, electrical and precision assembly. For each classification of work, classes are taken and certifications are updated on a regular basis. When new workers are brought on, they are trained formally in classrooms. The training usually lasts for 3-6 months. With the certification to perform different types of tasks, they start their on-the-job training (OJT) on the shop floor. In general, the immediate supervisor pairs the new worker with another worker to learn specific tasks. This process continues until the new worker is comfortable with enough work to keep busy. According to the crew chiefs, it usually takes 6 months to 1 year before an operator is fully capable of his or her job.

Table 3 rates different levels of training programs. This rating was developed based on how well information would be transferred from worker to worker. This evaluation applies only to the on-the-job training and not the certification and classroom training. (Observed ratings are bolded and this convention applies to following tables)

Table 3: Evaluation of on the job training in wing assembly

1. **Training done by worker performing a particular task**
2. **Training done by senior working with expertise in the task**
3. **Training done by workers knowledgeable in the task and who have training in instructing other workers**
4. Training done by qualified instructor
5. Training done by qualified instructor; each employee has training records for each work package and cross training program is implemented

Throughout the sites visited, it was found that all of the OJT was performed by fellow workers. These workers, although knowledgeable of the tasks, did not have any certification or standard procedures on how to train new workers. This informal training method does not ensure that operators learn all the correct practices and develop their skills systematically. Without this formal training, consistent work output and predictability of the system are compromised.

Standard Work

In any manufacturing process that includes people, the people are part of the process and their work must be defined with enough detail to ensure capability and repeatability. Standard work refers to two things: for every task, there is a correctly defined method for doing it, and every time the task is done, it is done in the same way. Although these statements may sound synonymous, one refers to having task definition (to be addressed under work instructions), and the other refers to the consistency of task performance.

To establish the extent to which tasks are being done the same way each time, three criteria are assessed: how tasks are performed by the operators from unit to unit, the sequence of assembly operations and the use of the standards and work instructions.

Table 4 summarizes the rating in each category by listing different levels of achievement in each category.

Table 4: Standard work rating in wing assembly

Performance of Manual Tasks
1. Operators perform tasks based on their own interpretation of the instructions or task description
2. Tasks are described at a high level so that low level movements are not described in detail but standard procedures are used for each type of task
3. Each task is described in detail so that it is done the same way each time
4. Work content is designed so that in can only be done one way
Sequence of Assembly
1. Entire assemblies may be built out of order (removing entire assembly which is delayed from a jig to start the next one)
2. Entire work packages may be done out of order (done out of sequence and/or out of station)
3. Assembly of parts in different sequences (e.g. Sequence of attaching parts, A-B-C vs. A-C-B, or sequence of tightening fasteners)
4. Assembly tasks are usually done in the correct sequence
5. Methods in place to prevent out of sequence work
Use of Standards/Instructions
1. Standards/instructions not used by operators
2. Standards/instructions used when learning new tasks or when tasks change
3. Operators are familiar with standards/instructions and keep themselves updated frequently
4. Operators are familiar with standards/instructions and are active in updating and improving them

Performance of Manual Tasks

At the micro level, standard work refers to the actual movements of the operator. In actual practice, two workers may perform the job correctly but with slightly different methods (such as which fastener to install first). These differences may cause increases in variation of the worker output. In the descriptions of performance of manual tasks, level 3 refers to describing the tasks in detail. The goal is not to document obvious motions but to provide enough information so that qualified workers have enough information to perform a task with repeatability. Level 4 refers to incorporating into the tools, parts or equipment, a design which allows only one way to perform a task (e.g. parts fitting together 1 way, fixtures which prevent errors, etc.). In airframe assembly, Level 2 was observed because the work instructions are designed for the operator to determine how to do the tasks that are described (e.g. Install part 123 as per blueprint).

Sequence of Assembly

At the macro level, standard work would be to perform all the major tasks in the correct order. This order however, is constantly being perturbed by work-arounds. These occur to keep assemblies moving and workers busy when part shortages, rework or other delays occur. Doing work out of order may produce assemblies that are within specification, but it introduces variability into the process and may be a cause of quality problems as operators are performing work in different orientations or making further installations more difficult. Throughout the sites observed, out of sequence work was common. Very often, work packages would be done out of order to keep workers busy. In extreme cases, entire assemblies would be built out of order. Levels 1 and 2 were achieved in this category.

Use of Standards/Instructions

Although there has already been a discussion of the work instructions, the use of them on the shop floor is also important. If operators are not familiar with them then the standards may not be kept. It is also important for the operators to use them so that they can verify their accuracy and keep them updated so that future workers will have the correct information to work from. This is important in a craft environment where there has been traditionally a lot of "tribal knowledge." Although some operators reported not using the work instructions, they were used for the most part by new operators, or when doing new tasks (level 2 achieved).

Mistake Proofing

It is inevitable that operators make mistakes even with the best training and levels of standard work. Because of this, it is important to design operations so that these mistakes are not translated into defects. Toyota referred to this as poka-yoke and designed stations that did not allow defects to be made. This practice is extendable to assembly and some examples were observed. Drills equipped with fixtures to ensure perpendicularity and maximum depth help workers to avoid making errors while drilling.

5.1.4 Methods

The design of the process plan is another source of variability. In this traditionally craft environment, much of the process is kept as expertise of the operators (tribal knowledge). To ensure that the process is well understood and documented, the work instructions may be evaluated.

Level of Work Instructions

Using Table 3 [Shields, 1996], the work instructions were rated. Throughout the sites, the work instructions were assessed to be either level 2 or 3. At this current level of work instructions, new tasks will require teaching from a more experienced operator. At one of the sites, the instructions were being updated to include pictorials of assemblies as well as more detailed diagrams. This effort was still under progress at the time.

The most critical component about the current level of work instructions is that much of the detailed procedures is not documented. The rationale for this of course is that the workers are skilled enough to translate higher level instructions to smaller tasks. It is not required for each movement to be described. The time required to do so would also be great. However, for this extraneous knowledge to be preserved in the shop floor, if it is not documented then it must be captured otherwise. As employees retire or transfer out, much detailed knowledge would be lost and have to be relearned.

Table 3: Work instruction rating in wing assembly

Work Instruction Rating	Definition (each level adds additional information to the level above)
1	Low level of detail consisting of only the blue prints and no written instructions
2	**Blue print data with information about changes to the drawings and some written instructions**
3	**Blue print data with changes identified and information about the effectivity of those changes readily available and written instructions for sufficiently skilled individual to accomplish the work**
4	All of the above with additional information about certain fabrication or assembly operations to include the use of pictorials for these details
5	All the above with added information in areas peculiar or easily confused instructions are supplemented with three-dimensional pictorials
6	All the above with the addition of photographs or pictorial drawings of correctly fabricated or assembled areas as examples
7	All the above with process information, characteristics and restrictions imbedded in the instructions
8	All the above with detail that is sufficient to be used by workers with less skill training or experience
9	All the above with the addition of key characteristics for particular fabrication or assembly attention or measurement
10	All the above with the addition of real time access to multiple databases to capture information about the fabrication or assembly and the ability to enter prescribed data relative to the fabrication or assembly

5.2 *Throughput Time Variation*

Any process that has a high variation in throughput time will exhibit either late deliveries, or high levels of buffer time. Both of these have been observed in wing assembly. As the PSD decomposition shows, quality has an impact on throughput time variation. Once quality has been addressed, establishing a system to detect and respond to production disruptions and predictable production resources may further reduce throughput time variation. Figure 20 depicts the decomposition of *FR-112: Deliver products on time*, but only includes the next two levels for the purposes of this discussion..

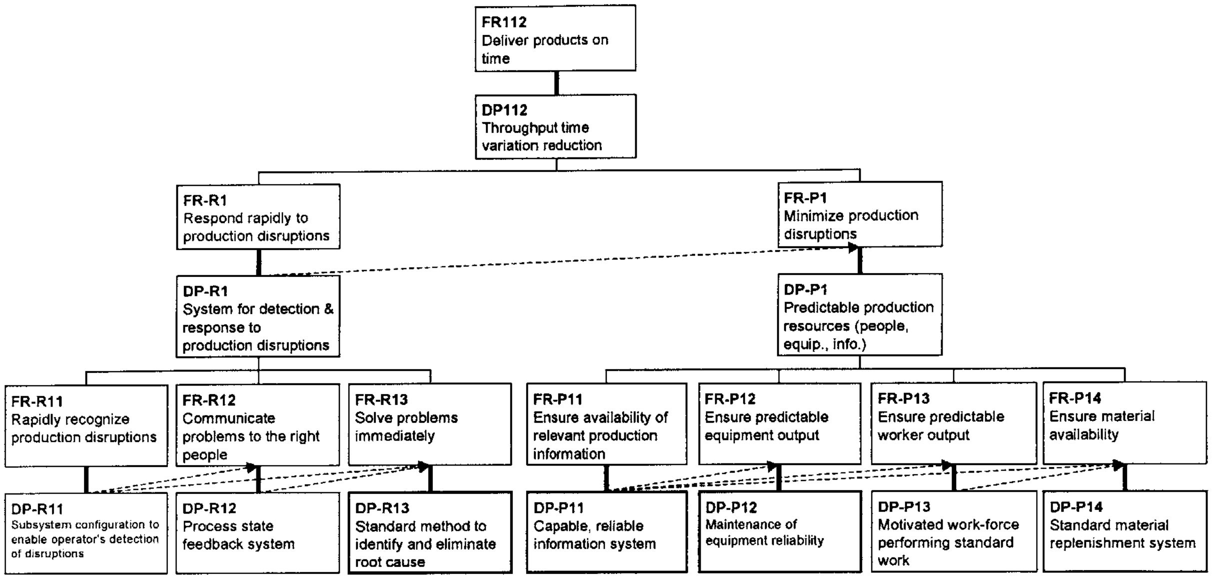

Figure 20: Decomposition of *FR-112: Deliver products on time*

5.2.1 Detection & Response to Production Disruptions

All of the sites visited had systems to document quality issues and prevent their reoccurrence (corrective action). Other production disruptions however, were not recorded formally or dealt with in the same manner. These included people availability, equipment or machines, planning and part shortages although resources were in place to deal with these problems. These other types of disruptions have great impact on throughput time variation and systems should be in place to eliminate them as well.

One observation concerning the corrective action procedure was that this practice was evaluated based on progress in handling the paperwork. Perhaps this performance metric should be changed to motivate the elimination of major production disruptions.

5.2.2 Predictable Production Resources

As the system is continually eliminating production disruptions, the production resources should also be designed to the predictable. These resources include information, equipment, people and materials.

Information

The information system referred to here is that which controls production. To ensure a capable and reliable information system, it should be simple to use and maintain. The MRP systems in place are able to plan resources but not to control production because it would require too much work to keep the system up to date. This is reflected by the expediting systems, recovery schedules and rescheduling observed among the sites. Simpler mechanisms should be put in place to coordinate production such as pull systems to coordinate part flow (as implemented in the engine sector [Ramirez, 1998])

Equipment

The large, monumental automated drilling machines were observed to be a source of delays and have the potential for significant production disruptions when down. Although these machines drill hundreds of holes with high tolerances, their complexity creates problems. This case is similar to the "Blohm Grinder" described in *Lean Thinking* [Womack and Jones, 1996]. The machines are massive and expensive, which require long set-up times, have faster processing times and require a support cast of technicians. By comparison, it may be beneficial to break down one complete, exhaustive drilling process to a number of simpler processes, to avoid putting all the requirements in one complex machine. There are many potential benefits in rethinking this process:

- Machines may be divided into different capabilities and simplified (as different sets of holes have different tolerances, separate installation of fasteners and sealing operations)
- Simpler machines may require less set-up time
- When one machine is down, the entire process does not have to be stopped
- Allows man-machine separation and cellular manufacturing

However, there are significant challenges as the increasing the number of set-ups may introduce more variability. If the tolerances may be decoupled from each other from station to station, it may alleviate this issue.

Workers

One of the achievements that Toyota has made in shop floor culture is their perfect attendance of workers. In their Georgetown, Kentucky plant, sixty percent of the workers had perfect attendance, which means that they were never late returning to their stations for even five minutes. As well, when workers are away, cross training within work teams ensures that the right people are always available.

As people availability was reported as a major source of delays, these types of programs should be implemented. At the sites that had people availability problems, there were regulations in place for taking days off. However, this system was not enforced causing unexpected people shortages.

Materials

Predictable part availability was found to be the critical factor in the engine sector study. It was also one of the major delays reported in wing assembly. As discussed above, pull systems were successful in simplifying the information required to supply parts, resulting in more predictable parts supply.

5.3 Throughput Time

Two of the tenets of lean production are to line up activities along a value stream and to make value flow smoothly [Womack and Jones, 1996]. Although implementing these ideas impact quality, the main objective is to decrease throughput time by eliminating waste and delays in the system. Much literature exists on the benefits of reducing throughput time, which may be summarized as reducing amount of inventory, less obsolescence, and responsiveness to changes in demand and design changes.

A further study on throughput time in aircraft assembly [Chao and Graves, 1998] quantifies the benefits of throughput time reduction from inventory carrying cost, revenue opportunity cost and variable tooling cost. The inventory holding cost is cash tied up in parts/materials, insurance, spoilage and obsolescence costs. Revenue opportunity cost refers to money lost in a market when a backlog of orders exists and customers pay upon delivery of the aircraft. If throughput time is decreased and customers are willing to pay for earlier delivery, a revenue opportunity is created by the receiving payments earlier. Variable tooling cost savings occur when a work center can decrease its throughput time enough to avoid duplicating the station or adding more tooling to maintain the production rate. More detailed explanations on the calculation of these three benefits are presented by Chao and Graves [1998]. Thus, a major focus of this study is on throughput time of the wing assembly and the delays that impact throughput time.

Again, quality and the throughput time variation have strong impact on the mean throughput time (partially shown by Figure 9). In addition to addressing these issues, throughput time may be further reduced by eliminating the delays in the system. The PSD decomposition identifies the following delays to throughput time: run size delay, process delay, lot delay, transportation delay and systematic operational delay as shown in Figure 21.

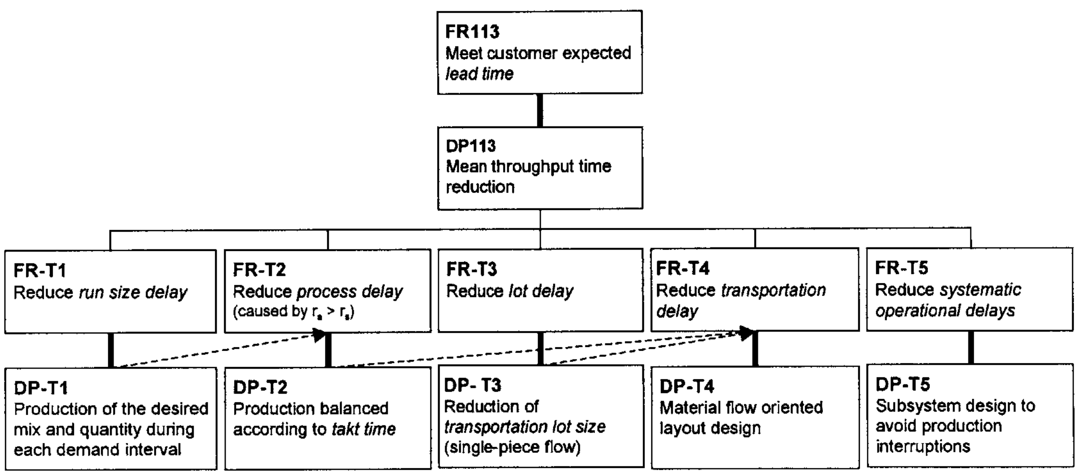

Figure 21: Decomposition of *FR113: Meet customer expected lead time*

In wing assembly, where single piece flow is used and production is synchronized to customer orders (each wing is customized to a customer), run size, lot and transportation delays are minimized. Systematic operational delays include operators having to disrupt their work to obtain supplies or other resources. A case study on eliminating these delays is presented in the next chapter.

5.3.1 Mean Throughput Time Reduction in Aircraft Industry

As this section of the decomposition is very integral to the definition of lean production, some more effort will be spent on discussing its applicability to the aircraft industry. Even though aircraft usually have very long throughput times, the same principles apply in decreasing them.

Run size delay

Run size delays occur when different part types share a resource. Traditionally, to reduce the setup costs, large run sizes would be used to decrease the setup cost per part. In doing so, large levels of inventory would collect before and after the process, adding to the throughput time.

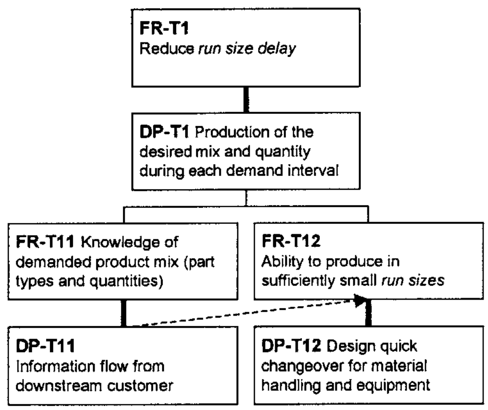

Figure 22: Decomposition of *FR-T1: Reduce run size delay*

Reducing run size delays involve the production of each part type within the demand interval. To do so, information from the downstream customer is required as well as the ability of the equipment to change over between different part types quickly.

Process delay

Process delay occurs when the arrival rate from an upstream process is not equal to the service rate of its respective downstream process so that entire lots form a queue while the station/machine is busy. To eliminate this delay, Toyota paced its supply chain to operate according the rate of final assembly, which was the takt time. If cars were being built one per minute, then its components were built at one per minute as well in a linked cell manufacturing system. In American mass production plants, components would often be aggregated for economies of scale with components built at a rate of one per 6 seconds, feeding multiple lines. In this type of production where the production rate increases and decreases, large amounts of inventory collect, adding to the throughput time. Figure 23 explains balanced production through the decomposition of *FR-T2: Reduce process delay.*

Balancing production to a takt time in aircraft production is challenged with long takt times (weeks, instead of minutes). Theoretically, each part required would then be produced at a rate of one per week. Again, if setups are avoided and run-sizes are large, then this requirement would not be met. Process delays are produced when a system is unbalanced. Chao and Graves [1998] discuss how throughput time may be reduced by eliminating the number of parallel stations. This can be done by designing fewer parallel stations that have more people. This practice supports having all the stations running to the same takt time.

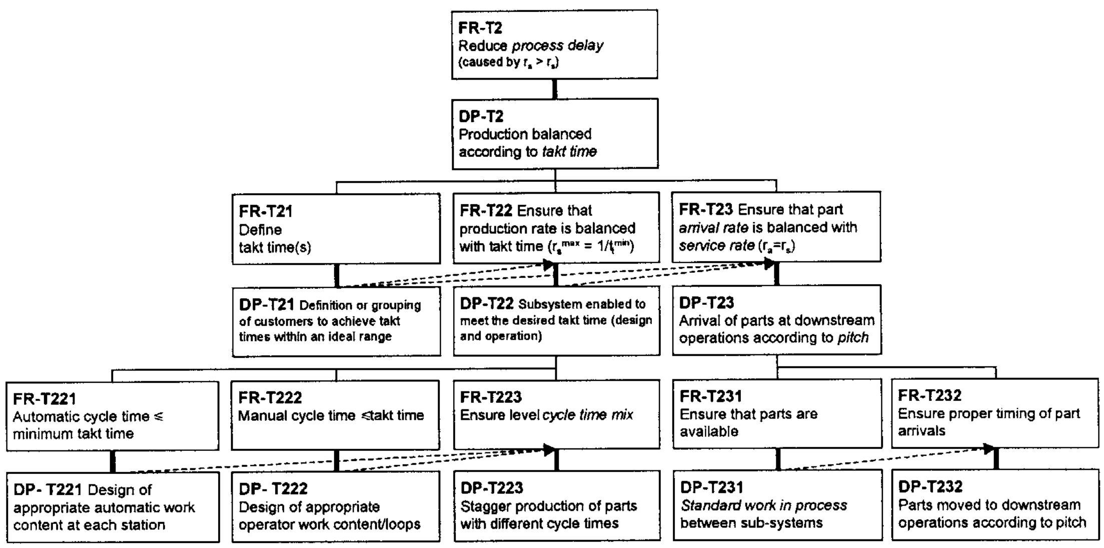

Figure 23: Decomposition of *FR-T2: Reduce process delay*

Lot delay

Lot delay occurs when one part of the lot must wait for all the others to be processed before the entire lot can be advanced and can be reduced by changing to single piece flow.

Transportation delay

Dealing with the issue of transportation delay is a significant challenge in the aircraft industry. For the most part, the geographical locations of the supply chain for a given aircraft are not drawn as a "spaghetti diagram" throughout a plant, but one that spans the country and in some cases, the world. There are many reasons for this inefficiency that Todd and Simpson [1986] present. First of all, aircraft components and assemblies are very expensive and so have low relative transportation costs. So, to obtain parts from across the country or overseas adds little to the overall cost. However, throughput time may suffer if scheduling or production problems occur. Assembly plants are located across the country based on many factors including the availability of a local skilled labor force and even political considerations for military programs. Parts fabrication is generally centralized as each location has different capabilities. An example is the large forgings and sheet metal skins that are sourced by only a few presses that serve the entire industry.

A common practice in the sale of military aircraft to foreign governments is offset packages where portions of the aircraft are built in the contracting nation to provide jobs and industrial development to justify the foreign spending. The result is that plants are transplanted and assemblies are shipped from overseas. Even commercial programs have international supply chains with entire subassemblies being delivered overseas and across the country.

To change the infrastructure and mentality of an industry that considers geographical location a minor factor and does not think twice about sending parts back and forth across the globe would take a colossal effort. In lean production transportation is deemed waste. Though the infrastructure may be a present constraint, changing the mindset may allow future opportunities for reducing transportation delay. As technology changes, opportunities may arise to streamline the supply chain. The increasing use of composite skins and machined structural parts may allow co-location of fabrication centers and assembly plants.

Systematic Operational Delays

As mentioned, interference between material handling tasks and assembly tasks increasing throughput time can be reduced by decoupling these tasks so that material handlers ensure parts are located near the station to avoid an interruption in the assembly task.

5.4 Production Cost

Once quality, throughput time variation and mean throughput time have been addressed, large reductions in production costs should already be achieved (impact of quality on labor cost shown in Figure 8). In addition, elimination of wasted efforts by direct and indirect labor will further reduce costs as depicted in Figure 24.

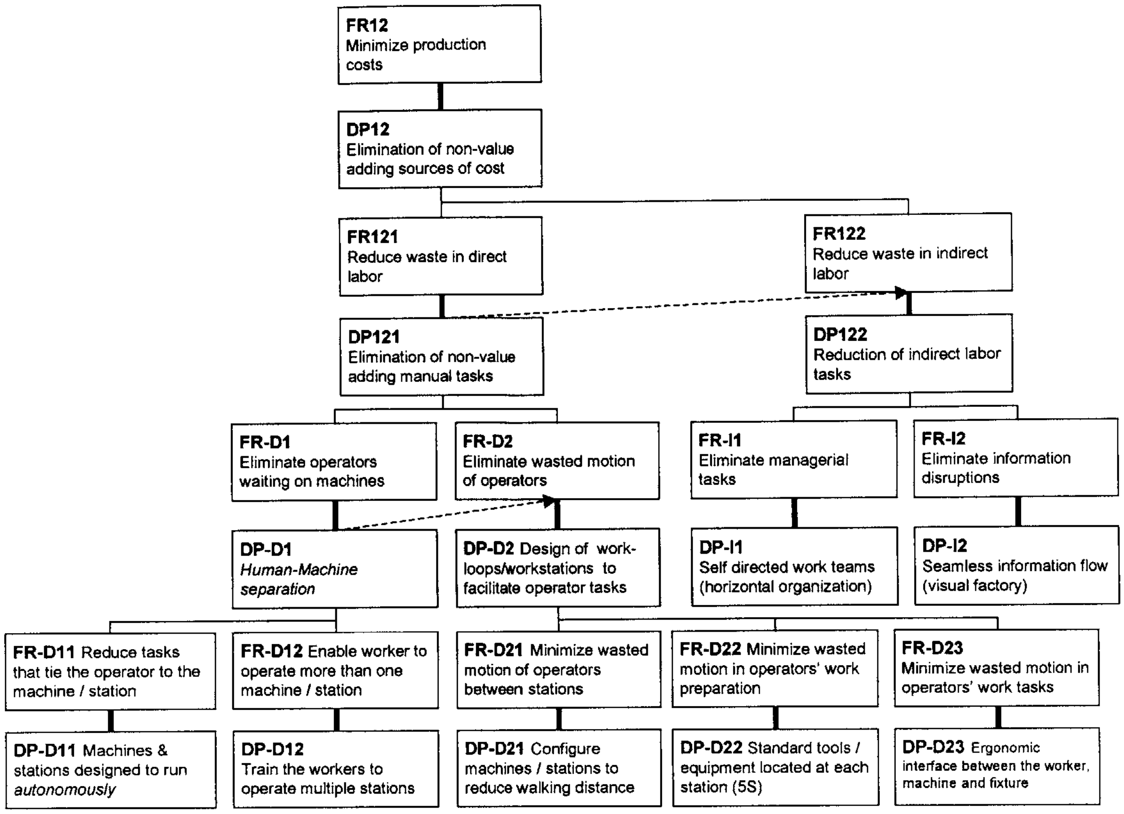

Figure 24: Decomposition of *FR12: Minimize production costs*

5.4.1 Elimination of Non-Value Adding Manual Tasks

Eliminating tasks such as walking around to get supplies and tools has been addressed in throughput time reduction.

5.4.2 Reduction in Indirect Labor Tasks

As workers become more responsible, self directed work teams may be implemented to reduce the amount of supervision required. This idea was observed to be in progress at some sites.

The high levels of expediting observed also add to the indirect labor cost. The information system must be designed to allow fabrication to know the actual needs of the assembly lines without extensive intervention.

5.5 Investment

Many of the decisions that impact investment are made from the requirements in quality, time variation, throughput time and production costs. Taking these considerations in mind, the goal of minimizing investment is to satisfy those requirements while making decisions that decrease the system's life-cycle investment cost.

By simplifying the machines as discussed, the investment cost may be comparable or actually increase. However, the premise is that machines that perform a smaller range of tasks (less complex) may have greater flexibility for different products (machines which do many tasks on different types of wings would be enormous). This ability to reuse equipment may decrease the system lifecycle investment. Also, as technology improves and the processes are updated, replacing or improving one of the machines would be easier than incorporating the change into an already complex machine that performs many tasks.

Another issue is capacity planning. In the military programs where tooling is paid for up-front, all the tools may be purchased early in the production cycle. This practice adds wasted cost (not to the company though) if the production rate does not reach expected levels if the demand is changed. This issue should be addressed by altering the procurement policies to promote the acquisition of investment incrementally. Another benefit to adding tooling incrementally is that improvements or resolution of problems may be incorporated into the next set of tooling. Further analysis of procurement policies on the manufacturing system will also be elaborated on in chapter 7.

5.6 Summary

The PSD decomposition was used in this chapter as a framework for analysis of the wing assembly systems. This analysis was useful in highlighting potential improvements in the production system design and the different implications that lean principles have in the aircraft industry. Comparisons made within individual sites (from chapter 3) also supported the relationships between quality, operator work, throughput time and cost as identified by the PSD decomposition. Further refinement of this decomposition may continue to provide insight into the design of lean production systems in the aircraft industry.

The greatest challenge in airframe assembly is to achieve stable processes while fitting together parts of high dimensional variation. Although this problem must also be addressed through design, training and standard work aimed at capturing the techniques used by experienced workers to fit the parts together with minimal variation can help to stabilize production.

In airframe assembly, there were many sources of unpredictable production disruptions observed, but the manufacturers were still able to meet their planned throughput times, which suggests that the planned throughput times have been established to accommodate the time variation. This variation may be addressed by applying formal methods to track and eliminate the cause of production disruptions as has been established for quality.

Studying actual/planned throughput times in airframe assembly did not yield a similar contrast as seen in the engine sector. All sites were observed to have schedule buffer built into their systems, which made actual/planned throughput time a poor comparison metric in this case. More importantly, there were no major systematic differences observed between the sites as in the engine sector, (a site using pull system for parts supply) which would cause a major contrast in performance.

One of the differences in operations was the practice of sending incomplete wings to final assembly accompanied with workers to complete the tasks out-of-station. There was a significant correlation between the amount of out of station work and total direct labor hours. Further impact to quality, the work in final assembly or to the work center that was missing workers has been reported but was not quantifiable with the available data.

One of the observations made was the existence the informal systems in place to supplement the MRP system. These were the expediting and recovery schedule practices. The existence of these systems suggests that the design of the information systems are inadequate to control production and relate the actual demand from assembly to fabrication.

Chapter 6: Experiences in Lean Implementation: B-2 Case Study

In the wing assembly study, the states of multiple systems were analyzed. Although some differences were found, it was difficult to compare the performance between different systems. The focus was on what the states of the system are but not how to change them. This chapter will focus on this issue of how changes can be made and on what their benefits are. This is done with the approach of examining a process before and after lean implementation projects and analysis using the PSD decomposition. By doing so, companies may assess the impact of potential projects in their own systems. In addition to studying the potential benefits, the strategy and methods of applying these projects is also discussed to provide further insight into implementation issues.

At the fall 1998 LAI plenary Factory Operations Breakout Session, Northrop Grumman presented their experiences with lean production and some of their implementation projects on the B-2. They focused on the elimination of non-value added tasks for operators in an attempt to shorten throughput time, decrease cost and improve quality. They reported immediate benefits in all of these areas. The factory operations group decided that this provided an opportunity to study their methodology, execution and results providing valuable insight into implementing lean production in the aircraft industry [12].

6.1 Background

The B-2 is a low-observables strategic penetration bomber [Jane's Information Group Ltd., 1998] designed in 1981 and the military had planned to purchase 132 aircraft. This program was eventually cut and only 21 B-2's were built increasing the expected unit cost by three fold. Currently, production of these aircraft are complete and they are all in service.

[12] The site visit for this case study was performed by Daniel Dobbs, also a member of LAI and the PSD laboratory. Thanks to Dan and the participants from Northrop Grumman for their contribution to this study.

Northrop Grumman is currently in the process of updating all planes to the Block 30 configuration, but this should be completed by June of 2000. Future business from the B-2 program is expected to come from PDM (product depot maintenance). Northrop hopes to receive the contract to perform this work instead of having it performed by the Air Force at Tinker AFB. This bid for future business is the condition that has set the stage for implementing lean production. The classical "crisis" situation is setup because there is a possibility of losing the business in the future. This uncertainty provides an additional motivation for shop floor workers, engineers and management to accept a new approach.

6.1.1 Scope of Study

As the aircraft have already been completed and are in service, the nature of the work studied differs from the assembly tasks from the wing assembly case study. The primary business unit (or "cost center") studied was the Low Observabilility (LO) area. This area performs eleven processes required to provide the proper surface finish to ensure low observability of the aircraft. The tasks involved are cleaning, stripping and the application of tape and fillers. Although the nature of the work is different from assembly tasks, it is still characterized as highly skilled manual work content in the aircraft industry.

6.2 Methodology

6.2.1 Strategy

A "lean implementation team" was selected by the vice-president in charge of operations at the Palmdale facility. As opposed to many other approaches that advocate working with the shop floor workers in improving the process, a team of managers and engineers helped to implement the initial stages. Direct employee involvement was avoided to focus the scope of the projects at the beginning. More employee involvement was solicited after the first major changes and feedback and suggestions were used to further improve the process.

Again, the Program Depot Maintenance (PDM) program was identified as the area that would most benefit from applying lean production, which is the program that Northrop Grumman hopes to win the contract for, guaranteeing business for as long as the B-2 program is in active Air Force service. As a prototype project, one of the Low Observability cost center would be addressed first.

6.2.2 Timeframe

The projects started in July of 1998 and are still continuing. The main thrust is expected to be completed by August. A new production control system will be in place at the end of April. The new system will help coordinate material supply for the specific processes that are being performed. For example, the list of tasks that must be performed can be entered into the system and the system will list the processes required and the kits and materials needed for the processes.

6.2.3 Lean Implementation Team – Initial Effort

After establishing a lean implementation team with four full-time and four part-time members, from manufacturing engineering, production control, management and quality control, consultants were hired to help develop a lean implementation plan. After some training in the philosophy behind lean production, a test project was used to start the program off.

The lean implementation team started by videotaping a a tape application process used to seal and fill in gaps around the entire surface of the plane to evaluate the technician's movements. This is to identify waste and develop standard work guidelines. Using this process highlighted the amount of time the technician spent away from the station where she was working to retrieve materials, mix adhesives and perform other tasks in preparation to apply the actual tape. Problems in ergonomics were also highlighted, as the platform she was using was not long enough for the area she had to apply tape to.

To alleviate the excessive amount of time retrieving materials, the team created a kit that contained the tools and most of the materials needed by the technician for a job. The material handlers also became responsible for much of the preparation work and delivered mixed adhesives and precut tape when required. A more suitable platform was also installed to eliminate repositioning in the middle of the task. With drastic reductions in throughput time the and elimination of non-value added tasks, the lean implementation team was ready to apply these methods to the rest of the Low Observability area.

6.3 Analysis

Kits and Material Handlers

The aircraft is divided into five sections, each of which is the responsibility of one team of technicians. Every morning, each technician picks up a kit that contains the tools and most materials they will need for the process they are performing. The kits are divided into two halves. The "A" half contains tools such as a flashlight, measuring tape, knife and stopwatch (to time curing). The "B" half contains consumable items, such as a notepad, disposable applicators, cleaners, solvents and water. Included in each kit are also the work instructions. This allows the technician to stay at the work station instead of spending time acquiring the necessary materials. Figure 25 illustrates the change in the amount of walking necessary by the technicians (*DP-D22 Standard tools / equipment located at each station – 5S*).

In this redesigned work pattern, the role of the material handler changed. Instead of operating the various materials, tool and parts cribs, they are responsible for creating the kits. In doing so, there was no increase in the number of material handlers. The roles of the technicians changed as well. Within each team, one member would be responsible for the materials preparation such as trimming the tape and mixing the adhesives. Again, there was no increase in the number of technicians. The material preparation tasks and application tasks were separated so that a worker would not have to stop working on the plane *(DP-T51: Subsystems and equipment configured to separate support and production access req'ts*). Instead, workers called for the materials they would need ahead of time so that they would be delivered ready to apply when needed. The PSD decomposition identifies these DPs as physical implementations that decrease throughput time and production cost.

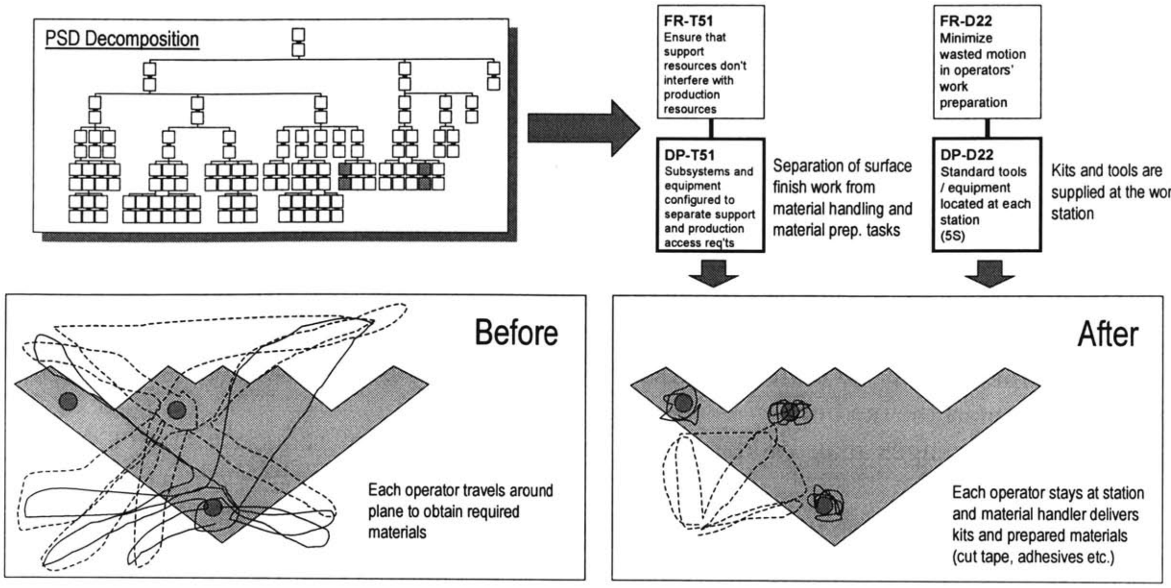

Figure 25: Kitting and material handling redesign on the B-2

Standard Work

As discussed in chapter 5, standard work refers to two things: for every task, there is a correctly defined method for doing it, and every time the task is done, it is done in the same way. Although all companies have some methods to ensure standard work, improvements on the Low Observables process captured the special techniques used by the technicians that were not documented before.

The standardized work was determined by observing many technicians performing the same operation and taking the best practices observed. Before the kits, many workers made their own tools to help them with their work. The best of these tools were copied and included in the kits. The use of common tools and standard work helped to improve consistency between different workers performing the same process. Analysis of the level of standard work shown in Table 5 shows that higher levels of standardization were achievable in the tape application process.

Table 5: Standard work evaluation for B-2[13]

Performance of Manual Tasks

1. Operators perform tasks based on their own interpretation of the instructions or task description
2. Tasks are described at a high level so that low level movements are not described in detail but standard procedures are used for each type of task
3. **Each task is described in detail so that it is done the same way each time**
4. Work content is designed so that in can only be done one way

Sequence of Assembly

1. Entire assemblies may be built out of order. (removing entire assembly which is delayed from a jig to start the next one)
2. Entire work packages may be done out of order (done out of sequence and/or out of station)
3. Assembly of parts in different sequences (eg. Sequence of attaching parts, A-B-C vs. A-C-B, or sequence of tightening fasteners)
4. **Assembly tasks are usually done in the correct sequence**
5. Methods in place to prevent out of sequence work

Use of Standards/Instructions

1. Standards/instructions not used by operators
2. Standards/instructions used when learning new tasks or when tasks change
3. **Operators are familiar with standards/instructions and keep themselves updated frequently**
4. Operators are familiar with standards/instructions and are active in updating and improving them

Compared with wing assembly, which involved the fitting of high tolerance parts, greater work content variation and more parts, the low observable process is less complex and perhaps easier to standardize. However, the improvement in standardization within the process has an impact on quality, time variation and throughput time as shown in Figure 26.

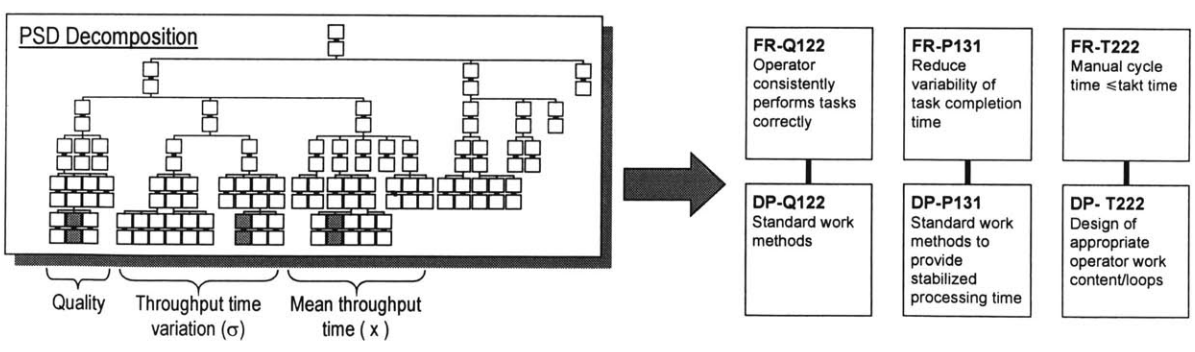

Figure 26: Impact of standard work in the system

[13] Observed ratings are bolded

Standard work is a design element that satisfies many FRs, which is a physical integration of functionally independent (or decoupled) requirements [Suh, 1990].

Work Instructions

As the work was being standardized, the work instructions were redesigned as well, providing much more detail in describing *how* tasks are done instead of stating *what* needs to be done. The work instructions are rated in Table 6 using the same rating system [Shields, 1996] as in chapter 5. The rating of the work instructions did not differ significantly from the wing assembly sites. However, the written descriptions were more detailed in describing how the tasks are to be performed.

Table 6: Work instruction rating in wing assembly[14]

Work Instruction Rating	Definition (each level adds additional information to the level above)
1	Low level of detail consisting of only the blue prints and no written instructions
2	Blue print data with information about changes to the drawings and some written instructions
3	**Blue print data with changes identified and information about the effectivity of those changes readily available and written instructions for sufficiently skilled individual to accomplish the work**
4	**All of the above with additional information about certain fabrication or assembly operations to include the use of pictorials for these details.**
5	All the above with added information in areas peculiar or easily confused instructions are supplemented with three-dimensional pictorials
6	All the above with the addition of photographs or pictorial drawings of correctly fabricated or assembled areas as examples
7	All the above with process information, characteristics and restrictions imbedded in the instructions
8	All the above with detail that is sufficient to be used by workers with less skill training or experience
9	All the above with the addition of key characteristics for particular fabrication or assembly attention or measurement
10	All the above with the addition of real time access to multiple databases to capture information about the fabrication or assembly and the ability to enter prescribed data relative to the fabrication or assembly

[14] Observed ratings are bolded.

Ergonomics

In order to improve the ergonomics for the technicians, new scaffolding and platforms were purchased. Before the improvements, operators had to kneel on top of the wing to perform all operations above the wing and had to stand on narrow platforms or lie on their backs to perform all operations under the wing. The new platforms allow the workers to remain standing for operations performed on the top edges of the wing and for all operations under the wing. This change illustrates *FR-D23: Minimize wasted motion in the operator's work tasks* being satisfied by *DP-D23: Ergonomic interface between the worker, machine and fixture.*

6.3.1 Impact

Improvements were measured using the metrics of throughput time, actual labor hours, rework and overtime. Data from the four units before the projects and five units after the projects was available for analysis.

Rework

Comparison of the before and after units show not only a decrease in the total number of rework hours, but also decreased rework as a percentage of total actual labor hours as shown in Figure 27. The mean of the before and after samples are 12.3 % and 5.9% respectively, a decrease of 52%. It is expected that the decrease in rework hours, (quality improvement) has an impact on the variation in throughput time and mean throughput time, which collectively impact production cost.

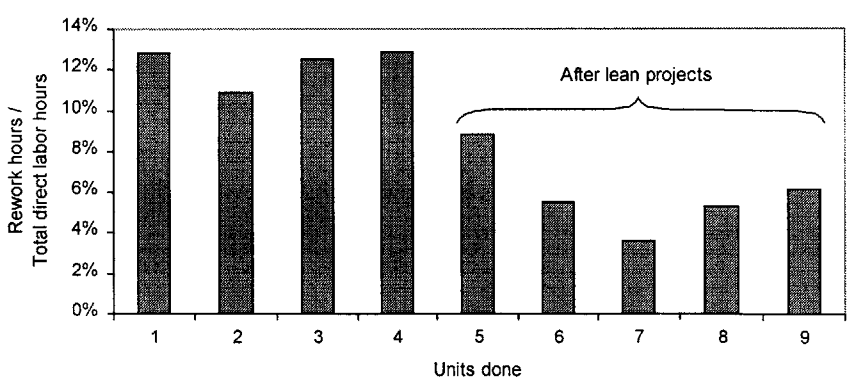

Figure 27: Rework hours / total labor hours – before and after lean

Overtime

Overtime may be viewed as an indicator of throughput time variation if it is used to make up the time lost when unforeseen production disruptions arise (when it is not planned). Again, comparison of the before and after units show a decrease in both the total number of overtime hours as well as a percentage of total actual labor hours as shown in Figure 28. The mean of the before and after samples are 12.5 % and 6.5% respectively, a decrease of 48%. This decrease in overtime hours, (time variation reduction) is also expected to impact mean throughput time and production cost.

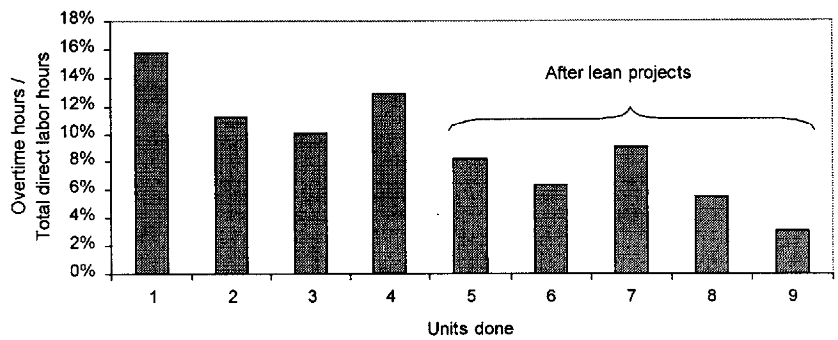

Figure 28: Overtime hours / total labor hours – before and after lean

Throughput time

The throughput time of the process decreased on average by 24% between the two samples but this must be moderated by the fact that the throughput time showed a general decreasing trend (except for one point) before the lean implementation projects. To test whether this difference in the mean of the two groups is statistically significant, the following hypothesis was tested,

> H_0: *There is no statistically significant difference in the mean throughput times of the two samples (before and after the lean projects: m1 – m2 = 0)*
>
> H_1: *otherwise; there is a statistically significant difference in the mean throughput times of the two samples (before and after the lean projects: m1 – m2 ≠ 0*

The null hypothesis could not be rejected with a 95% confidence interval so the difference in mean throughput time is not statistically significant. This result is due to the large variation in throughput time of the sample before the lean projects and the low number of samples.

Even though the results are not statistically significant, there was still an observed decrease in throughput time and the variation in throughput times decreased. The first unit to undergo the lean projects also showed a continued decrease in throughput time even though it included the process of setting up the kits and improving the work standards. As the throughput time continued to decrease, the operating pattern changed from 5 days a week to 4 10-hour days a week (on last 2 units).

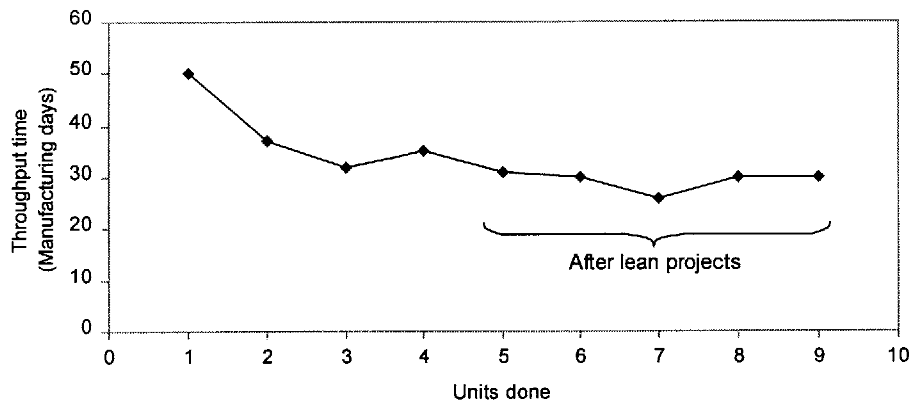

Figure 29: Throughput time – before and after lean

Labor Hours

Comparing the mean of the total labor hours from before and after the projects, there was a mean decrease of 40% for the process. Although this figure sounds like an incredible improvement, there are a few factors to consider. Firstly, these processes, like in airframe assembly have a natural amount of learning so that the total labor hours should decrease after each successive unit as shown in chapter 3 (equation 2). So, comparing the average of samples that are temporally separated would always give a decrease in mean shift. To account for the learning curve, the exponential curve was fitted to the first 4 units (before lean) in Figure 30. In this graph, it is obvious that the decrease in labor hours for the process decreased beyond the amount that would be expected from normal learning. In fact, after the lean projects, the actual labor hours were on average 21% less than the trend projected from the units before the projects.

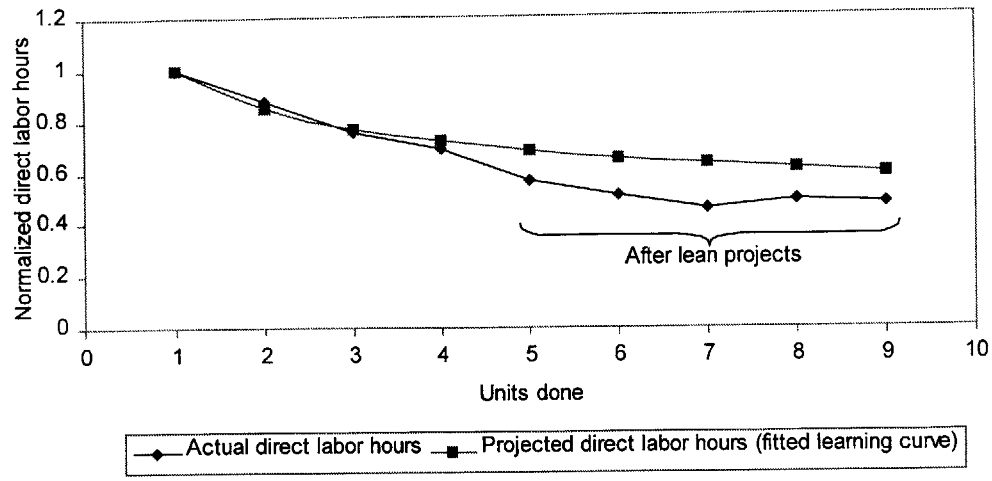

Figure 30: Total labor hours for tape application process before and after lean projects (exponential learning curve fitted to first four units)[15]

6.4 Discussion

6.4.1 Reaction to Change

The most difficult part in the implementation was reported to be the change in the corporate culture. Overcoming the resistance to change was difficult and success was attributed to strong leadership and support from the highest levels of the organization. It was also reported that difficulties arose when trying to apply changes beyond the scope of the cost center where the lean projects were being focused.

In retrospect, it was reported that it would have been helpful to train the entire facility in lean production first to prevent the problems encountered outside of the cost center being changed. Making improvements by process rather than cost centers would have been easier to implement.

6.5 Summary

In providing kits and prepared materials to the operators, these tasks were not eliminated but decoupled from the technician. Instead of the technician interrupting their tasks for material

[15] Labor hours normalized by dividing each value by maximum observed value to obtain a ratio.

handling and preparation tasks, another worker does them in parallel so that the value-added tasks are continuous. However, the amount of walking away from the stations was isolated to the material handler and all the materials necessary were centralized for them. Further improvements in ergonomics, work instructions and standardization were also applied. These lean implementation projects showed significant decreases in the amount of rework (52% decrease), overtime (24% decrease) and total labor hours (21% decrease compared to expected reductions). The throughput time variation decreased as well.

A LEM evaluation of this site is also included in Appendix E as a reference.

Chapter 7: Beyond Factory Operations[16]

In order for lean production to be implemented, throughout the literature the role of upper management and leadership is established as the first step. Monden [1998] defines in his *Introductory steps to the Toyota Production System* the first step as, *Upper management plays a key role.* As aircraft companies embrace lean production and establish upper management approval/facilitation and "lean implementation teams," a fundamental influence – the procurement policies – must be addressed in military aircraft programs. Throughout history, the military has played a key role in the development and sustainment of the aircraft industry to ensure that the country's production capability is maintained. Although the Air Force has been supportive of lean production, the procurement policies that regulate how programs are selected, established and paid for have great impact on the production system's design and operation. Regardless of the intentions of leaders of the manufacturers and the Air Force, the procurement policies constrain the design of the production system and motivate sub-optimal practices.

This chapter will identify how the procurement policies have impacted existing aircraft programs and how it has established barriers for lean production. By understanding these influences, the design of the policy issues may be rethought providing opportunities to overcome traditional barriers and creating motivation for "lean" production system design.

7.1 Special Factors in Military Aircraft Programs

7.1.1 Product Performance and Quality

To ensure that the US Air Force has a tactical advantage over its opponents, military aircraft are designed to possess the most advanced capabilities available. The product design and development teams take an aggressive approach to design a product with the most impressive

[16] Much of this analysis was based on discussions with Tom Shields and Cliff Harris who provided valuable insights into military procurement policies and how they impact the practices of manufacturers.

specifications possible. In fact, in programs with long development times, technology that has not been achieved yet will be incorporated or relied upon expecting that it will be mature when required. Although this approach makes products more difficult to build, it ensures an aircraft that will meet aggressive Air Force requirements, ensuring further demand.

After the development process, when the units are being used in service, changes are often requested to improve performance. Changes also occur to incorporate new technology. These changes were a common problem during WWII [Zeitlin, 1995] when combat experiences demanded many changes which disturbed the regular manufacturing process. A balance was eventually sought so that the planes would be kept as competitive as possible without debilitating the manufacturing process. Engineering changes were incorporated after each production block (50 – 500 units) [Vogt, 1999]. At the Willow Run plant, these changes made more than half of the jigs and fixtures obsolete.

In addition to product performance, quality is another requirement. Reliability in military aircraft is a critical factor as product failures may result in loss of life or failure of a mission. To ensure that the products are of the highest quality, 100% inspection is used involving inspectors from manufacturing and even from the government. In addition, any quality issues (non-conformances) that may compromise structural integrity are fully analyzed by engineering and reworked accordingly. These non-conformances must often go through an approval cycle by the government as well.

7.1.2 Production Investment

The proposition of going through the design and development process of a military aircraft, purchasing all the tooling, materials, parts, and hiring all the employees necessary is a daunting and risky one for any manufacturer. To alleviate these problems the government becomes what may be viewed as the prime contractor and sets the requirements for what is needed and then pays for the development of those aircraft. These contracts have been traditionally cost-plus programs during design. When production is being ramped up, the government also pays for all the tooling and test equipment necessary up-front. One of the reasons for this is the bidding process for contracts. Even before production begins, an estimate of the investment cost is required before the project is approved. With an accepted proposal, the manufacturer is then expected to build all the tools necessary at the estimated investment cost.

Although this practice allows manufacturers the resources to proceed with development and manufacturing of the aircraft, it may inadvertently motivate inefficient practices such as tooling where it may be unnecessary, and acquiring equipment and material too soon.

7.1.3 Cost Negotiations

Once production begins, the aircraft are typically ordered in lots. The price per aircraft for subsequent lots is negotiated based on the current actual manufacturing costs and the trend in cost reduction. It is expected that the costs will reduce for each subsequent lot of aircraft. The government has access to all the cost data so that a fair price can be set for the next lot.

Although this strategy decreases the cost of each lot to the government, it may not decrease the long-term production cost. As manufacturers try to decrease their risk, they will try to ensure that the projected costs are attainable. To ensure the cost of parts and materials, high risk parts (long lead time, high cost items) are ordered well in advance so that those costs are posted as actuals prior to negotiation. If the parts were ordered after negotiation, there is risk that the price will be higher than what was allocated to obtain them.

Because cost savings do not result in profit but lowered cost to the customer [Harris, 1999], the approach to cost reduction will be more conservative. High risk, high payback projects are not attractive because any savings are passed to the customer but the manufacturer is responsible for cost overruns. This situation will promote low risk, low payback cost reduction projects to be implemented.

In the introduction, it was stated that airframes have long design life cycles so that cost reductions have a long payback period. However, cost based pricing constrains investment recovery. In annual procurements, a cost reduction investment may not be made unless it is paid back within the negotiated period. This deters potentially worthy projects from being implemented.

To capture the impact of these factors on the production system, a design decomposition of the existing system through axiomatic design illustrates how the policies create conflict in how the upper level FRs of a production system are satisfied.

7.2 Axiomatic Design Analysis of Military Aircraft Production Systems

Using the axiomatic design approach introduced in chapter 4, a design decomposition of how the procurement policies impact the production system design will be developed in this section. Although the decomposition presented in this chapter will not capture all of the dynamics of the business strategy, it will highlight the different incentives in the military aircraft industry to the production system design. This can then be compared with the PSD decomposition to illustrate where conflicts arise.

The first step is to identify the customers who are the government, the shareholders of the manufacturing companies, the employees of the company and the local community. The needs for these customers are summarized in Table 7. In order to satisfy all of these customer needs, a product must be designed and delivered to the Air Force with the desired capabilities, quality and cost. The product must be produced by a company that is making a profit and creating jobs that are fulfilling, rewarding and safe for its employees. To establish the top level FR-DP pair, the most comprehensive requirement will be for the company to maximize return on investment with a well designed production system. In doing so, secure jobs are created, profit is made and a desired product is delivered to the government.

Table 7: Customer Needs

Customers	Needs
Shareholders	Return on Investment
Government	Resources to defend country and maintain an industrial base
Employees	Jobs, compensation, safety, work environment and job satisfaction
Local community	Local economy and environmental concerns

With this as the top level FR-DP pair, the decomposition is continued from the perspective of the company as they make many of the decisions about the design of the production system. Again, the top level DP is decomposed to the elements of ROI as depicted in Figure 31. Note that the m-subscripts differentiate these FRs and DPs from those in the PSD decomposition.

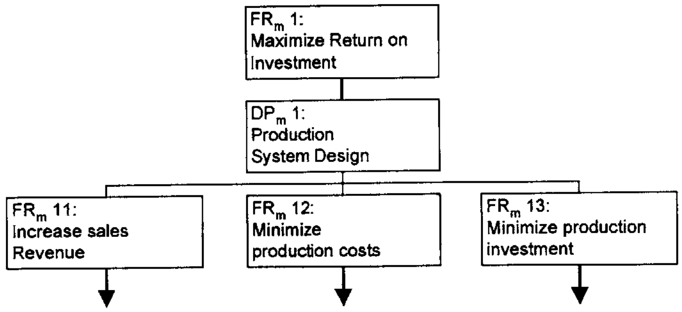

Figure 31: Top Level decomposition (military aircraft impact)

7.2.1 Increase Sales Revenue

The increase sales revenue branch is depicted in Figure 32. The main difference in military aircraft is the focus on product performance instead of how they are produced. Instead of *DP11: Production to maximize customer satisfaction*, (from the PSD decomposition – no defects, delivery on time, meet expected lead-time) the focus is more on *DP_m11: Products to maximize customer satisfaction* instead. This difference in focus is no surprise since design factors outweighing manufacturing and schedule factors is a trend that has been instilled in the aircraft industry since its inception.

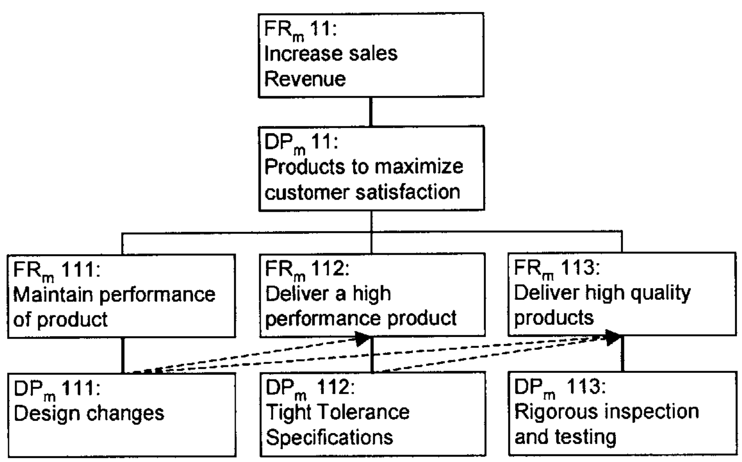

Figure 32: Decomposition of *FR_m11: Increase sales revenue* (military aircraft impact)

Although product design and capability have traditionally dominated how successful a program is, the way a product is produced is becoming more important. The time when product performance overshadowed budget and schedule considerations may be over.

As the military is moving away from *DP_m11: Products to maximize customer satisfaction*, further decomposition shows many practices that may still be in place. The need to keep products at top performance creates constant design changes that disrupt production. Even during war times when aircraft were being produced at high rates, production was constantly being disrupted with implementation of design changes. Upgrades to give these aircraft a tactical advantage in speed, range, armor and other abilities improved performance but increased aircraft cost dramatically.

The aggressive design and high performance of the aircraft demands that very tight tolerances be specified, which makes the products more difficult to build. These design problems are now being addressed with DFA and DFM techniques.

Lastly, due in part to the high product complexity and low volume, instead of stabilizing processes, quality is maintained through rigorous inspection to detect errors and painstaking rework to correct them. This adds waste in making the error, looking for the error and then repairing it.

7.2.2 Minimize Production Cost

In the PSD decomposition, to minimize production cost, *DP12: Elimination of non-value adding sources of cost* is selected. In military programs however, since the cost or aircraft per lot is negotiated based on actual cost performance on closed lots, a more complex dynamic is in place. For the manufacturer to minimize their production cost, they want to ensure that the production cost is equal to or less than the negotiated as shown in Figure 33.

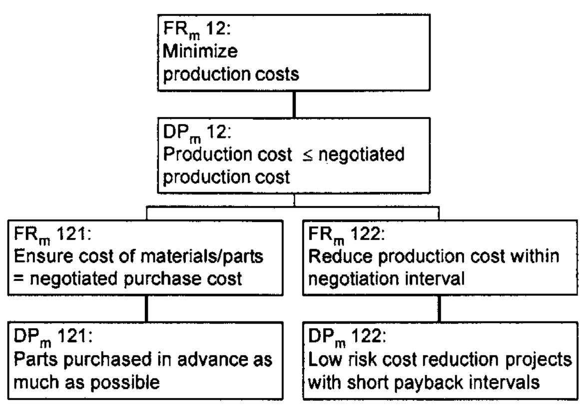

Figure 33: Decomposition of *FR_m12: Minimize production costs* (military aircraft impact)

To minimize the risk of obtaining a negotiated cost which is too low, manufacturers are motivated to ensure the cost of their materials, and that the cost projections are attainable.

One method to ensure the cost of materials, expensive parts or high-risk items (where cost varies) will be predictable is to purchase these items far in advance so that they will have been paid for before negotiations for the next lot. This practice makes the parts/materials a fixed cost, which is then paid for accordingly and eliminates the risk of an unexpected increase in the price of a part or expectations from the government to negotiate prices with suppliers.

To further ensure that production costs are less than or equal to the negotiated cost per lot, *FR_m122: Reduce production cost within negotiation interval* must be achieved. To satisfy this FR, cost reductions with a much shorter time frame are implemented. In addition, because companies are responsible for cost overruns but pass on long term savings to the customer, high risk/high payback projects are avoided.

In the military aircraft industry, reducing production cost has less direct impact on return on investment. Aside from product performance, a company that can demonstrate operational efficiency may be more likely to win new contracts and/or have existing contracts extended. However, long-term savings in production cost are passed on to the customer so the company has difficulty in justifying investments to reduce long-term cost when the investment will not be recovered by the company. If the cost savings may be realized within the production lot (since the price is already fixed) the savings do translate to profit so the company may justify those improvements.

During negotiations, the government does fund projects to reduce production cost. However, because aircraft are procured annually, the payback for the investment is short-term. Projects with longer-term payback periods are often not considered.

By negotiating contracts on an annual basis, *DP_m122: Low risk cost reduction projects with short payback intervals* will be the result, which does not decrease the long-term production cost of the program.

7.2.3 Minimize Production Investment

To minimize production investment, manufacturers can consider two things, the investment that is paid for by the government (tooling, test equipment, assets) and the investment paid for by the company (machine tools, facilities etc.). For a company to minimize their own investment, and reduce risks to their own production system they would choose *DP_m13: Utilization of government investment* as shown in Figure 34. This deviates from the adage of minimizing the total system life-cycle investment.

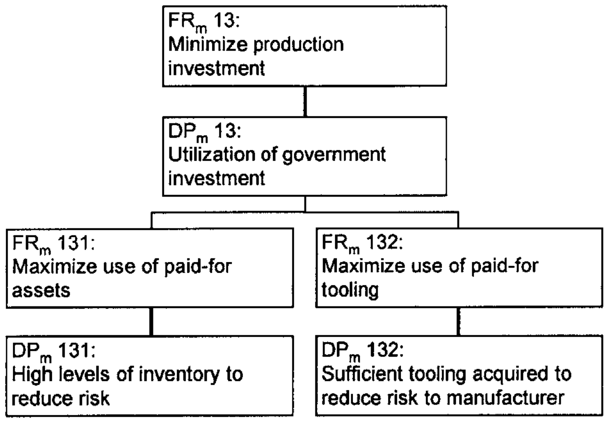

Figure 34: Decomposition of FR_m 13: Minimize production investment (military aircraft impact)

One part of the investment is the inventory or assets (referred to as waste by Toyota). As the inventory is paid for, the manufacturer has less incentive to minimize this waste and may hold excess levels of inventory as safety stock (*DP_m131*). This adds to the cost in storing and managing the inventory as well as increasing potential obsolescence costs as design changes are occurring often.

As the government pays for all the tooling before full rate production begins, manufacturers may acquire all the tooling necessary for the highest expected production rate (*DP_m132*). By acquiring all the tooling up-front, resources are wasted if the production rate does not reach expected levels (if the demand is changed). As well, by adding tooling incrementally, improvements or resolution of problems may be incorporated into the next set of tooling. Costs are also reduced in this case if the time value of money is considered.

7.3 Conflict with Production System Design Decomposition

The impact of the factors presented in this chapter on the PSD decomposition is discussed to highlight the conflict of the procurement policies on a production system designed with Lean principles.

7.3.1 Quality – Stable Processes

The focus on high performance in design and continual engineering changes makes establishing stable production processes very difficult. These changes make standardization even more difficult than it already is in airframe assembly. As the customer focuses more attention on the production as opposed to just the product performance, manufacturing issues may gain influence in the design and development process.

7.3.2 Mean Throughput Time

By purchasing parts in advance and holding high levels of inventory there is a strong impact on throughput time. To alleviate this, incentives for manufacturers to hold a minimum of inventory may be implemented.

7.3.3 Production Cost

The annual contracts promote conservative and short-term approaches to cost reductions so *DP12: Elimination of non-value added sources of cost* may be difficult to implement to its fullest extent. Incentives allowing manufacturers to keep a portion of the profits from extra cost reductions and longer contract agreements [Harris, 1999] may alleviate this problem.

7.3.4 Production Investment

The procurement policies motivate the minimization of up-front investment cost, conflicting with the *DP13: Investment based on a long-term system strategy.* This policy must be carefully designed to promote investment that is flexible to accommodate the potential changes in design and production rate.

7.4 Summary

Using the axiomatic design approach, the impact of military aircraft procurement policies on the design of manufacturing systems is depicted in Figure 35.

In order to implement lean production to its fullest extent, the policies for procuring aircraft must be designed in a way to promote the elimination of waste and continuous improvement.

The role of these policies have played important roles in maintaining the strength of the aircraft industry throughout history but are now hindering effective production system design.

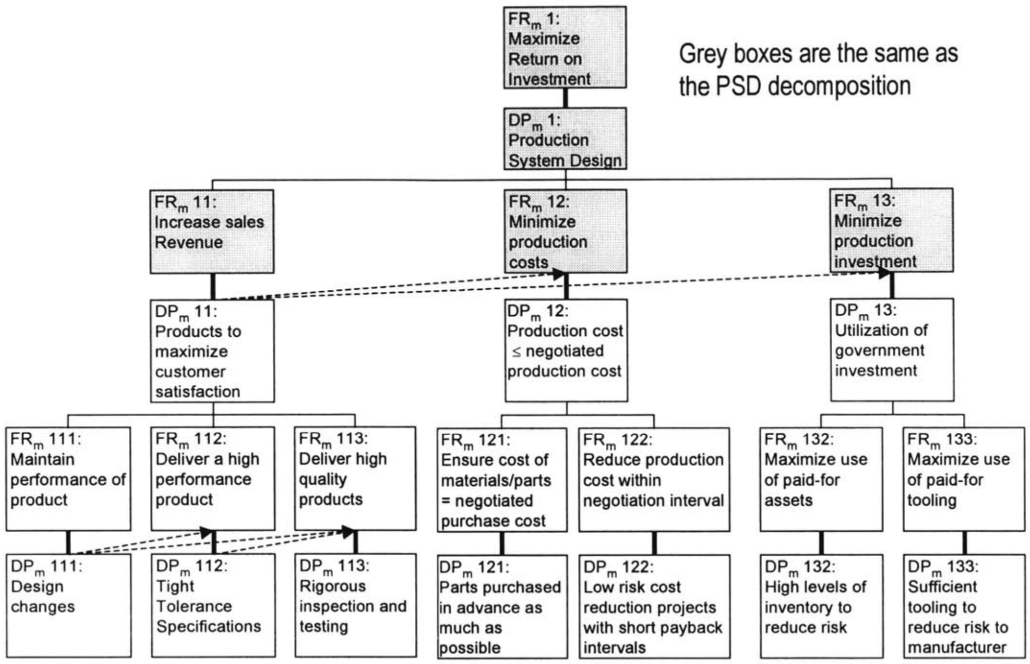

Figure 35: Military aircraft production decomposition

To deliver products with high performance, aggressive product design and continual design changes make products difficult to manufacture and creates production disruptions. Schedule and

To ensure that the production cost is less than the negotiated cost within the contract lot, manufacturers have the incentive to take conservative, short-term approaches to cost reduction. The motivation is to acquire parts and materials far in advance so they are posted as actual costs prior to negotiation, reducing the risk of unexpected price increases.

By paying for all of the investment up-front, the government creates incentive for acquisition of tooling before required and the minimization of initial as opposed to long term investment cost. As the assets are also paid for, there is no incentive to reduce the level of inventory.

In order to transform the way defense aircraft are produced, the policies must be rethought to eliminate incentives for sub-optimal operations.

Chapter 8: Production System Design Evaluation

In order for companies to convert their production system to one that is based on meeting the objectives of a "lean" production system design, the adoption of best practices is not enough. Instead, the production system must be intentionally designed so that the practices and elements of the production system integrate to achieve the business goals of the company. Presented in this chapter is a tool for companies to evaluate the design of their production systems. The methodology builds on the material on Axiomatic design and the PSD decomposition presented in Chapter 4, and the analysis in Chapter 5.

8.1 Motivation

8.1.1 Defining a "Good" Design

The first distinction that must be made is the difference between evaluating the design of a production system and measuring its performance. This can be a difficult distinction because designs often are evaluated based on performance. In addition, commercial value, cost, quality, innovation and customer satisfaction are also measures of successful design [Ulrich and Eppinger 1995]. In manufacturing, many factors may contribute to the success or failure of the venture including product design, marketing, distribution etc. that may be outside of the realm of manufacturing. To assess the production system based on performance of the product does not indicate how well the production system is designed, operated and what the potential for improvement is. To address these questions, the goal is to evaluate the production system based on how well it is designed.

In concept screening/selection approaches, the designs/concepts are assessed by how they impact the many requirements or design criteria. A similar approach exists in an Axiomatic design process where analysis of how the design parameters impact the functional requirements. Evaluating how well the functional requirements are satisfied will be used to assess the production system design in this chapter.

8.1.2 Impact of Evaluation Methods on System Evolution

One theme of Prof. Cochran's [1998] Production System Design course is that production systems evolve based on the way they are measured. The classic example is the focus on machine utilization and direct labor costs. To ensure that machines are fully utilized, workers monitor the machines (one machine, one operator) to keep the uptime maximized. In addition, to decrease direct labor cost the speed of the machines are increased. The machine cycle time is unbalanced relative to the takt time and the high cost super fast machines are grouped into departments to promote utilization. Throughput time, inventory, and quality traceability are all sacrificed. The Toyota Production System addresses unit labor cost reduction by grouping machines by product family, with workers operating a number of machines [Cochran, 1998]. In this configuration – usually cellular – machine utilization may be lower but the machines are simpler and may be reused. In this design, inventory and throughput times are low, quality issues are discovered as they occur, the numbers of workers may be reduced, and there is greater flexibility.

The impact of performance metrics on production system design also exists in the aircraft industry. One example is that the cost accounting systems track labor hours. At one of the sites visited, touch labor accounted for only about 10% of the operating cost yet it was the most widely used measure of manufacturing performance. Managers often promoted "work-arounds" (out of sequence work) when a production disruption occurred to keep workers busy but it introduced variability into the process and masked the visibility of the production disruption.

These examples in the automotive and aircraft industries illustrate that the metrics used to measure performance do not improve the system design but rather improve operations. The premise being that by optimizing each operation individually, the resulting sum improves the system, which could be no further from the truth.

8.1.3 Current "Lean" Production Assessments

As the implementation of lean production becomes more widespread, companies and consultants have developed methods to evaluate how "lean" a production system is. The evaluation charts observed in the automotive and aircraft industries (including Toyota, TRW, Ford and Visteon) are very similar in nature. They rate manufacturing based on a number of criteria, which may include management involvement, levels of inventory, scheduling methods, implementation of cells, standardization, man-machine separation and shop floor attitudes. In each of these categories, levels are defined which qualitatively describe achievements from poorly operated "mass" production to the ultimate in "lean" production as depicted in Figure 36.

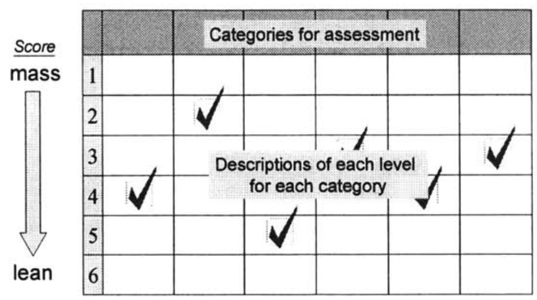

Figure 36: Typical Lean Evaluation Chart

These evaluation tools are designed to allow someone ("lean expert" or production management) to visit a manufacturing plant and through simple observation, make an assessment on how "lean" the system is and where improvements should be made. This can be done because many of the elements of TPS are visible, such as U-shaped cells, kanban, single piece flow, standardization, visible by standardized inventory and work-pace.

Although these assessments indicate whether a manufacturer "looks like" Toyota and give some direction for improvement, they do not clearly indicate the relationships between the elements to effectively evaluate the design of the production system. To do so, an evaluation tool derived from the Production System Design decomposition presented in Chapter 4 will be presented.

8.2 Methodology

8.2.1 Development from PSD decomposition

As described in Chapter 4, the PSD decomposition applies axiomatic design to a generalized production system using the principles of TPS. Using this model, certain FRs were selected as the criteria for evaluating the system design. Figure 37 shows the mapping of the selected FRs to the evaluation tool criteria. The evaluation criteria are FRs and the DPs are evaluated by how well they satisfy the FRs. In general, the FRs selected were in the fourth level of decomposition (except for quality and production investment). The first 3 levels are descriptive of the business strategy of the production system as opposed to its design. The major areas that are evaluated are, stable processes, time variation, delay reduction, direct labor cost, indirect labor cost and production investment. The evaluation FRs are selected at a level where the DPs are physical design elements in the system that are observable and thus may be evaluated. The evaluation FRs are also general enough so that they apply to almost all production systems.

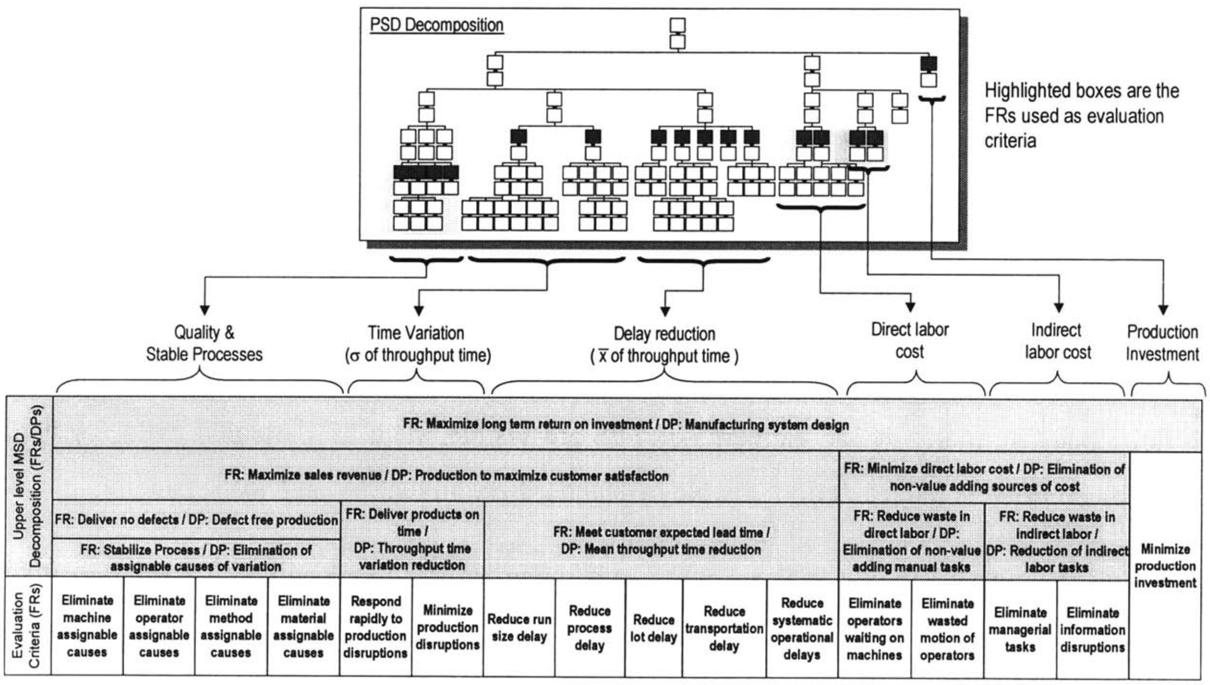

Figure 37: Mapping of evaluation FRs to PSD decomposition [Cochran et al., 1999]

Quality – Stable Processes

In the quality section of the PSD decomposition, the fifth level FRs were selected as evaluation criteria because they specify the elimination of assignable sources of quality problems from machines, operators, methods and materials. These four evaluation FRs provide more detail in achieving stable processes.

Throughput Time Variation (σ)

The next two evaluation FRs are the response to and minimization of production disruptions, which relate to throughput time variation. The system design in place to respond to production disruptions is important so those problems are found immediately and can be addressed so that the root cause of the problem may be eliminated to prevent the disturbance from reoccurring. The amount of production disruptions must also be eliminated by designing the system so that the resources (machines, people, information and materials) are predictable.

Mean Throughput Time ($\bar{x}$)

The next five evaluation FRs deal with the mean throughput time by the elimination of run-size delay, process delay, lot delay, transportation delay, and systematic operational delays. These delays are evaluated because they identify the wasted time a part spends in the system. Assessing these FRs identifies the large levels of inventory, complex part flow and scheduling, long transportation distances, and regular interferences in the system that must be identified and eliminated to reduce throughput time.

Direct Labor Cost

In labor cost, waiting on machines and the elimination of the non-value added tasks are evaluated. To separate workers from machines through autonomation was deemed a pillar of TPS and is important in environments where the processes are highly automated. Where manual tasks are more prevalent, eliminating the non-value adding tasks is important.

Indirect Labor Cost

To assess the indirect labor cost the elimination of managerial tasks and information disruptions are evaluated. Many levels of management increase the overhead cost and may add little value to the customer. In addition, if decisions must be reviewed by many levels, it slows decision making and improvement activities. To measure the elimination of management tasks, the extent to which self-directed work teams are implemented on the shop floor and in the support groups is assessed. Teams that are responsible for their own performance require less supervision. Information disruptions also cause indirect labor because people are necessary to react to them. Typically, more expediting and scheduling tasks are necessary when the information system has problems. The requirement for the support groups such as engineering (industrial, manufacturing), facilities, maintenance etc. are specified in the branches for quality, and predictable time output. Information disruptions and many levels of management within these groups also increase the indirect labor cost.

Production Investment

Finally, production investment is evaluated based on how well the machines/equipment accommodate the rest of the system design. The PSD decomposition shows that the design is path dependent. Therefore, the investment must support the design of the system to maximize customer satisfaction and reduce production cost. Machines should be right sized so that the cycle time is matched with the takt time of the cells or sub-systems. The equipment should also fit the layout and operation of the sub-systems or cells, being small enough to reduce walking distance to allow work-loops if necessary. Machines that are autonomous enables the worker separation is also important. Along with these factors, flexibility is an additional consideration that may reduce the overall system lifecycle investment. The amount of flexibility required depends on what is reasonably expected in product design changes, technological upgrades, and volume changes. Further discussion on the impact of other FRs/DPs on production investment may be found in section 8.4.2 as the interactions are elaborated on.

For each of the evaluation FRs selected, the next section describes how the qualitative assessments are developed.

8.2.2 Qualitative Assessment of FRs based on the Information Axiom

The information axiom [Suh, 1990] provides a way of measuring or comparing the performance of designs. It defines I, information content as a function of p the probability of satisfying a given FR as shown in equation 3.

$$I = \log_2 \frac{1}{p} = -\log_2 p \qquad \text{Equation 3}$$

So as the probability of satisfying the FR approaches 1, the information content approaches zero and thus, it is minimized. This logarithmic formulation is used so that information content may be additive when there are multiple FRs to be evaluated. The probability of satisfying an FR is usually calculated as the area of the system range (output) that lies within the design range (tolerance).

The goal is to develop a tool that may be used to evaluate the design of a system based on observation. Therefore, a method to qualitatively assess *p*, the probability of satisfying an FR is required. To do so, consider the *FR: Eliminate method assignable causes* shown in Figure 38.

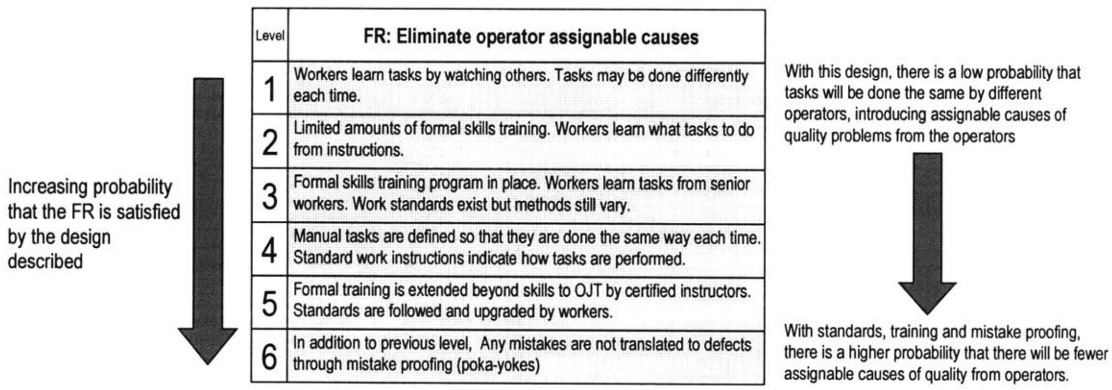

Figure 38: Example of qualitative assessment that an FR is satisfied

To eliminate assignable causes of quality problems from operators, each of the boxes describes approaches in which operators learn and perform tasks. In level 1, "Workers learn tasks by watching others." In this approach, there is a chance that the tasks will be done consistently each time but the probability is low. As the level increases, the gradual addition of standard work, instructions, training and mistake proofing increases the probability that workers perform tasks consistently, eliminating assignable causes of quality problems from operators. Although each level increases in probability of satisfying the FR, because the analysis is qualitative actual probability ratios are not assigned. Instead, a rating of 1 to 6 is used for simplicity. This same method is used in developing the descriptions for each FR identified as an evaluating criteria and is presented in the next section.

8.3 *PSD Evaluation Tool*

Figure 39 presents the PSD Evaluation Tool. It consists of 16 columns, each of which lists 6 levels of achievement in satisfying the FR indicated.

Upper level PSD Decompostion (FRs/DPs)	FR: Maximize long term return on investment / DP: Manufacturing system design ->							
	FR: Maximize sales revenue / DP: Production to maximize customer satisfaction ->							
	FR: Deliver no defects / DP: Defect free production				FR: Deliver products on time / DP: Throughput time variation reduction		FR: Meet customer expected lead time / DP: Mean throughput time reduction ->	
	FR: Stabilize Process / DP: Elimination of assignable causes of variation							
Evaluation Criteria (FRs)	Eliminate machine assignable causes	Eliminate operator assignable causes	Eliminate method assignable causes	Eliminate material assignable causes	Respond rapidly to production disruptions	Minimize production disruptions	Reduce run size delay	Reduce process delay
Level of Achievement (DPs) 1	Poor quality output from machines due to unknown causes of variation (unable to hold mean). No maintenance of machine to ensure quality.	Workers learn tasks by watching others. Tasks may be done differently each time.	Methods are unstable and ill defined. Variation in methods is arbitrary and is not visible.	High variation in incoming parts which cause quality problems. Materials are damaged in storage and transport	Production disruptions occur frequently. Operators work around these disruptions so they are hidden.	Unpredictable resources. Disruptions are frequent and impact delivery.	System is designed to operate based on forecast demand, not actual demand. Production in large run size batches to avoid the long setup times.	Machine capacity and rate independent of demand (maximize output). Large and unpredictable levels of WIP between processes to manage system and avoid starvation.
2	Some assignable causes of variation are identified. Maintenance is occasional and is not scheduled.	Limited amounts of formal skills training. Workers learn what tasks to do from instructions.	Methods are known but not documented (shop floor "tribal knowledge")	Parts arrive with questionable quality and must be inspected before use. Entire lots are sent back if there are bad parts.	End of line inspection is used so quality problems are found late. Slow response to problems.	Disruptions are frequent but do not impact delivery often due to large buffer sizes. Frequency and type of disruptions is unknown.	System is designed for production plan based on forecast demand. Run size is based on <1 month's forecast demand.	Machines/processes in functional departments are arranged for product flow. High levels of inventory required between departments (varying production rates)
3	Most causes of variation are identified but are still not eliminated. Maintenance is only in response to quality problems.	Formal skills training program in place. Workers learn tasks from senior workers. Work standards exist but methods still vary.	Methods have been defined and standards exist but are not always followed/ updated.	Supplier responsible for meeting specifications. Little inspection of incoming parts required. Some parts are still damaged within the plant.	Quick response to production disruptions (when they are found) to continue production. Root cause is not eliminated so problems may reoccur.	Machine disruptions (MTTF, MTTR) are recorded and used to determine lead time required for predictable delivery.	System is designed for production plan based on forecast demand. Run size is based on <1 week's forecast demand.	Assembly or transfer line designs running at high speeds feeding multiple customers. Large amount of inventory before and after lines to manage product flow
4	Most causes of variation eliminated, some causes are still unable to be removed.	Manual tasks are defined so that they are done the same way each time. Standard work instructions indicate how tasks are performed.	Methods are well defined and repeatable. Standardized and followed.	Supplier responsible for meeting specifications. Little inspection of incoming parts required.	Production disruptions are addressed quickly and the root cause is eventually addressed. In-process inspection.	Disruptions from machines/ equipment, people, parts and information availability are known. Systems being developed to make resources more predictable.	System is not based on actual demand. Run size is based on a schedule that repeats at one or greater than one day. External setup tasks are reduced.	Customers grouped to achieve effective takt times. Machines and people are capable of working to takt time. Some parallel processing/stations exist.
5	Causes of variation reduced so that machine output is stabilized and mean shifts rarely occur. Maintenance is scheduled and performed on time.	Formal training is extended beyond skills to OJT by certified instructors. Standards are followed and upgraded by workers.	When methods are improved or updated, they are documented and implemented.	Collaboration with suppliers to ensure quality. Material handling and storage designed to maintain quality of products.	System designed so that production disruptions are visible. In-process checks by operators so quality issues are found quickly. Good root cause analysis.	Systems designed so that disruptions from all resources are reduced. Includes perfect attendance, TPM, std. material supply and reliable information systems.	System supports actual demand and expected peaks. Produce exactly what is consumed by the customer on a daily or shift basis. Internal setup tasks are reduced.	Cells/sub-systems running at takt time with standard inventory of one between stations. Machines and people are capable of working to minimum takt time.
6	Machines able to maintain mean, within tolerances. All assignable causes of variation eliminated or controlled through a regular maintenance program throughout system.	In addition to level 5, Any mistakes are not translated to defects through mistake proofing (poka-yokes)	Methods are continually being improved and implemented throughout organization. All employees are knowledgeable about the most current methods.	Collaboration with suppliers to improve quality and involvement in developing specifications. Parts transferred and stored to prevent damage.	Co-location of cause and effect (simplified material flow) and systematic method for communicating, and solving problems. Line stop methods in use (Andon)	Production disruptions rarely occur. Throughput time variation is very low and predictable.	Production of the desired mix and quantity during each demand interval using Heijunka. Almost no setup required between part types.	Production balanced to takt time throughout value stream. Some flexibility to produce to different takt times. Minimum WIP between processes& sub-systems/cells.
Comments	Refers to quality reliability of the machines. Assignable causes are those that cause the process to go out of control and may be: tool wear/breakage, bearing failures, etc. Maintenance in this branch refers to that which maintains quality instead of those that prevent breakdowns.	Refers to attaining predictable quality output from the workers. This is done through training, defining and following standard work and preventing common human errors from translating to defects/quality issues.	Method's are how process are done and include assembly tasks and process plans for machining etc. To prevent variation, these methods must be defined and followed. (standardized)	Material problems may be from suppliers or from handling within the plant.	Production disruptions refer to machine breakdowns, quality issues, information, worker availability. This branch deals with how these problems are addressed and eliminated.	Predictable resources are required for minimal production disruptions. Total preventative maintenance (TPM) programs, perfect attendance, reliable part supply and and information are required.	Delay due to inventory when producing different part types. Setup time is the time to change between part types within a station. Knowledge of the part types required is necessary or large inventories of different parts are required. With accurate and timely info, only the parts required are produced.	Process delay occurs when arrival rate > service rate (unbalanced rates). Large and unpredictable levels are indicative of process delay. It is reduced by balancing to a constant and predictable takt time. Flexibility to produce to different takt times keeps system balanced when demand changes.
Metrics	# of non-conformances caused by machines	# of non-conformances caused by operators	# of non-conformances caused by method used	# of non-conformances caused by incoming parts	Average time required to eliminate root cause	# and time impact of production disruptions	Average run size	Cycle time / takt time of 1 for each station / system
	Process capability				% on-time delivery of parts / orders and variation of throughput time		Customer lead time and mean throughput time ->	
	Number of defects							
	Sales Revenue ->							
	Return on investment ->							

Figure 39a: PSD Evaluation Tool[17] (page 1 of 2)

[17] Developed as a continuation of the "Design Evaluation of a Lean Production System Design" [Cochran and Lima 1998], based on the PSD decomposition V5.0 [Cochran et al. 1999] (Appendix D). Thanks also to Jim Duda for his help and comments in developing this tool. Please contact Prof. Cochran for the latest version of this document and to discuss its application.

<- FR: Maximize long term return on investment / DP: Manufacturing system design							
<- FR: Maximize sales revenue / DP: Production to maximize customer satisfaction			FR: Minimize direct labor cost / DP: Elimination of non-value adding sources of cost				Minimize production investment
<- FR: Meet customer expected lead time / DP: Mean throughput time reduction			FR: Reduce waste in direct labor / DP: Elimination of non-value adding manual tasks		FR: Reduce waste in indirect labor / DP: Reduction of indirect labor tasks		
Reduce lot delay	Reduce transportation delay	Reduce systematic operational delays	Eliminate operators waiting on machines	Eliminate wasted motion of operators	Eliminate managerial tasks	Eliminate information disruptions	
Large transportation lot sizes between machines or processes to reduce transportation costs.	Mfg. Process focused layout. Machines arranged by function in isolated departments (job shop type). Complex material flow.	Processes must be interrupted frequently for routine tasks such as material handling, machine maintenance, chip removal etc.	One person, one machine design. Operator watches machine run.	Excessive walking required to search for tools and materials.	Vertical organization with many levels of management. Changes are slow to implement as they require review and authorization from many people.	No systematic information system in place. Difficult to understand production status.	Machines dedicated to part type are designed to run as fast as possible. Flexibility for future design and volume changes are not considered.
Single piece flow in only some areas (like assembly). Upstream processes still deliver materials in large lots.	Process focused layout with departments grouped to reflect product family sequence of operations. Parallel processing occurs. Routing is unclear. (focused factory)	Routine tasks are designed so that they may be done infrequently - loading lots of material, large reservoirs for chips, infrequent maintenance.	One person, one machine design. Operator waits on machine when running, or does "fill-in" work when available.	Excessive walking required to obtain tools and materials that are not located at point of use. Few improvement activities.	Management and support groups organized by function. Lengthy time is required for tooling changes, facility improvements etc.	Information system (MRP) in place but not all employees understand or trust it. Constantly erroneous or out of date.	High speed batch production machines dedicated to part families enables development of lower cost tools and fixtures.
Single piece flow in only some areas. Upstream processes deliver materials in lots based on standard inventory.	Product or customer oriented material flow. Machines/stations in cellular design with some batch processes/monument machines intermixed (partial cells)	Many routine tasks are scheduled so that they may be done after hours (like maintenance). Production still must stop regularly for other activities.	Operator runs more than one machine of the same type of manufacturing process. Machines do not have self-stopping capability.	Workers isolated to stations to avoid walking. Workers must prepare materials before adding value. Poor ergonomics causes worker to constantly reposition.	Support groups organized by product (IPT) and are co-located. Team members still evaluated by discipline.	Information system in place (MRP) to plan and schedule production. System requires team of expeditors and rescheduling to control production.	Equipment is reconfigurable to different part types. Machines still not designed to run at takt time in product oriented flow layouts.
Single piece flow within cells/sub-systems. Large lots transferred between sub-systems.	Material flow/cellular design with machines/stations close together. No monument machines that complicate material flow (well defined cells)	Machines/processes designed so they do not have to be interrupted for routine material replenishment, chip removal and work preparation.	Operator runs multiple machines of different types with self-stopping capability. No operator-process work routine defined.	5S program implemented so that parts, tools and equipment are where they are required. Some improvements in ergonomics are made.	Members of support group teams are dedicated to products. Teams formed on the shop floor and understand their basic performance measures.	Visual displays are installed. Not all employees understand how the display represents the factory status.	Ergonomics improved so that several machines may the operated by one person. Machines allow cells but are not right sized and so cause excessive walking.
All cells/sub-systems using single piece flow. Transfer lots sizes between sub-systems being reduced based on demand interval.	Material flow oriented layout design applies throughout value stream. Minimum handling with process close to receiving and shipping docks. (linked cells)	Workers continually make improvements in eliminating interference between people, material handling, maintenance etc.	Multi-skilled operator runs several machines/ processes. The operator-process work routine time graph defined and used.	Workers continually make improvements to decrease wasted motion and improve ergonomics. Machines are small and close together to allow reduced walking distances (in cells).	Work teams track their own performance and accept responsibility for maintaining and improving them.	A standard system for visual management is in place. All employees are trained in use of the system.	Machines support layout and operation (cells, autonomation). Equipment has product flexibility and is reusable.
Single piece flow of parts throughout the factory.	Reduced transportation throughout supply chain. Production near customer and supplier base. Material flow oriented layout throughout plant.	Processes rarely ever stop for routine activities.	The operator- process work routine defined and used. Number of operators may be varied to achieve a range of takt times. Machines run autonomously	Level 5 applied throughout company in addition to 5S understood by all employees and applied beyond the shop floor.	Self directed work teams are fully accountable for their performance. Applied across shop floor and support groups.	Most information about the system may be derived visually and understood by all the employees. Abnormalities get quick reaction by the correct people.	Machine designed to run at a range of takt times. In-house capability to modify standard machines quickly when required.
Lot delay refers to parts waiting on other parts in the lot before they are transported together. This is avoided with single piece transport. Reducing transportation distance is important to achieve this.	To reduce transportation delay, the amount of transportation should be minimized. In system design, this is a consideration in factory layout. This is also applicable from a geographical view as well as within the plant	Operational delays are routine disruptions designed into the system (processes stopping for maintenance, material replenishment and other processes). It may be eliminated through machine and station design (Chip removal, control access from rear of station), operator work routine design.	Applies in fabrication or assembly when parts require multiple processes using different machines. Autonomous machines stop automatically when cycle ends or when a problem is detected.	To eliminate wasted motion, walking distances are deceased, 5S applied so tools, materials are readily available and ergonomics are improved.	This branch deals with the development work-teams, reducing the amount of management required. In the support groups, teams refer to the integration of engineers, production control, management, quality, scheduling. Their ability to make changes in order to support production is important.	To reduce the amount of tasks required to process information, visual management is used to simplify the system. This only works well when everyone understands how it works so that they can keep it accurate and respond to abnormalities when required.	Investment decisions are largely dependent on how the system is designed. Equipment should support this design and have the flexibility for expected volume changes, design changes and layout reconfiguration changes (cycle time/product flexible & small/movable machines)
Transfer lot size	Distance parts must travel through system	% of time down for routine tasks	% of time waiting on machine	% of time required for movement	% of employees in self directed work teams	% of system managed visually	% of value-added capital investment % of machines operating at or less than takt time
<- Customer lead time and mean throughput time			% of value adding operator time		% of indirect employees		
<- Sales Revenue			Production Cost				
<- Return on investment							

Figure 39b: PSD Evaluation Tool (page 2 of 2)

The top 4 rows show the top levels of the PSD decomposition, showing how each column is related to the overall system design. In each column, specific terms or additional explanations are provided in the "comments" row. The bottom 5 rows are suggested metrics that mirror the FRs. For each FR, a metric was chosen to quantitatively track the progress in satisfying each FR. The structure of the PSD evaluation tool is depicted in Figure 40.

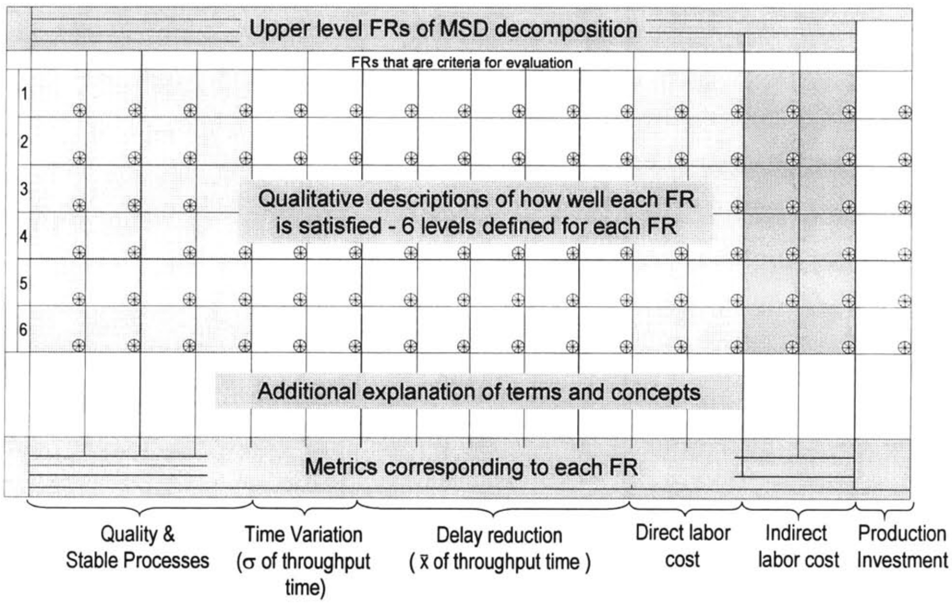

Figure 40: Structure of PSD Evaluation Tool

8.4 Analysis using PSD Evaluation Tool

8.4.1 Evaluation

Before evaluation of the production system may begin, the system in question must first be defined. This may be one area of the plant, a cost center, cell or an entire plant. Regardless of the scope of the system, it should first be well defined.

After the system has been defined, an evaluation is made in each column. The system is matched with the most appropriate description and marked using the pie-charts. If different portions of the system fall into different levels, the pie-charts are used to indicate the relative proportion of the system described. Figure 41 provides an example of how the pie charts are used and how comments explaining the evaluation may be done.

	Reduce process delay	Notes:
1	Machine capacity and rate independent of demand (maximize output). Large and unpredictable levels of WIP between processes to manage system and avoid starvation.	3/8ths of the plant is still organized as a job shop with machines running at independent rates.
2	Machines/processes in functional departments are arranged for product flow. High levels of inventory required between departments (varying production rates).	
3	Assembly or transfer line designs running at high speeds feeding multiple customers. Large amount of inventory before and after lines to manage product flow	1/8th of the plant (line A) is running as a transfer line feeding cells B, C and D. Large amounts of inventory after the line are required so that the cells are not starved.
4	Customers grouped to achieve effective takt times. Machines and people are capable of working to takt time. Some parallel processing/stations exist.	One half the plant has been organized into cells running at takt time but have not achieved standard inventory of one between stations.
5	Cells/sub-systems running at takt time with standard inventory of one between stations. Machines and people are capable of working to minimum takt time.	
6	Production balanced to takt time throughout value stream. Some flexibility to produce to different takt times. Minimum WIP between processes& sub-systems/cells.	

Figure 41: Example of evaluating an FR using the pie-chart system

Note that the sum of the pie-charts should sum to 100% for each column, representing the entire system. Some of the columns may not apply in all cases. For example, run size delay applies when there is production of a mix of parts and some columns deal only with machines, which may not always be used. After each FR has been evaluated, analysis may continue by studying the design matrices.

8.4.2 Interactions

To continue analysis after the evaluations have been completed, this section presents figures that show the relationship between the FRs that are evaluated and how they impact the other FRs and DPs in the system. The figures in this section also depict the design matrices implicitly using dashed arrows to show secondary relationships between DPs and FRs. This analysis may provide further information on what is required to implement

Quality – Stable Processes

If nothing else in the system is changed, stabilizing the process will have the largest impact and is almost a pre-condition for lean production. For companies where the process has not yet been stabilized, further decomposition shows the elements that introduce causes of variation. Figure 42 shows the FRs used as criteria in the evaluation tool and the upper level FRs and DPs that are impacted.

Stabilizing the process further impacts *FR112: Deliver products on time* and *FR113: Meet customer expected lead time*. If quality problems arise and defects are produced, time is required to make a replacement and to address the problem. If these problems are random, then the variation and mean in throughput time is increased.

Further impact to *FR12: Minimize production cost* shows the effect of making defects on production cost. As well, it is recognized that many of the methods to eliminate causes of variation require resources such as engineers and support to develop standard methods, work instructions. However, the design shows that they are required and that production cost is not minimized by eliminating these efforts, but focusing on eliminating non-value added sources of cost.

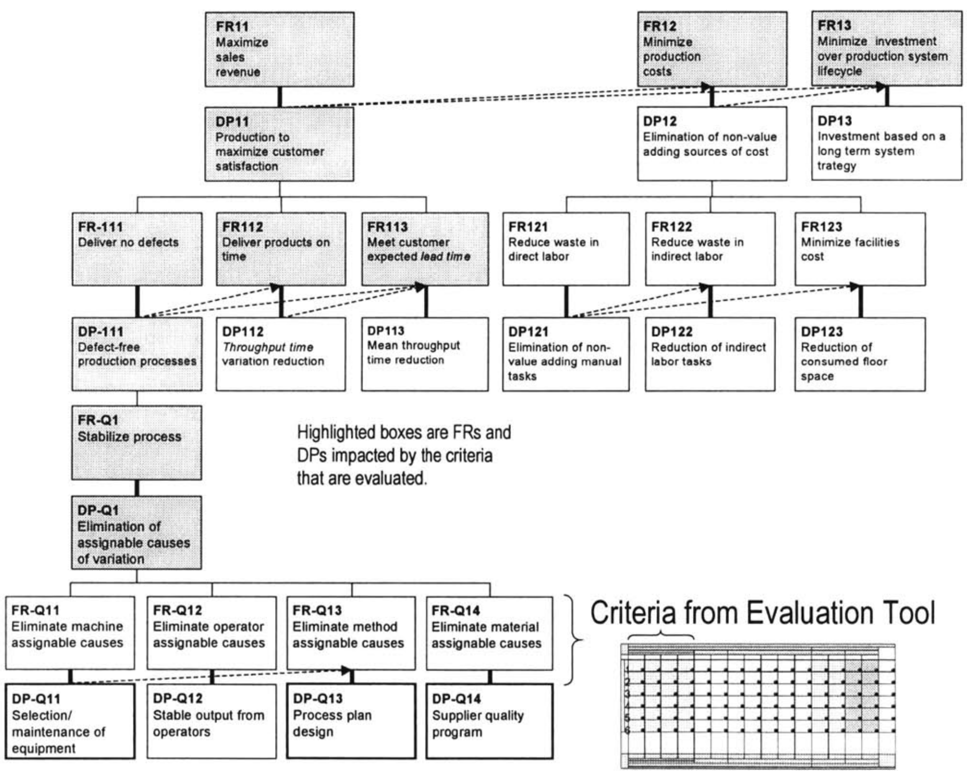

Figure 42: Interactions of quality – stable processes

The interactions also show the relationship production investment and quality. Evaluation of the investment must consider whether the machines are capable of stable output.

This analysis shows how stable processes have the most impact on the system. This relationship is not something new to lean production but must be achieved to satisfy the system requirements.

Throughput Time Variation (σ)

The criteria evaluated to reduce throughput time variation shown in Figure 43 are the quick response to production disruptions and minimal disruptions through predictable resources. From the decomposition, *DP-R1: System for detection & response to production disruptions* impacts *FR-P1 Minimize production disruptions.*

As the variation of throughput time decreases, the customer lead time decreases even if the mean throughput time is unchanged. Impact to production cost comes from setting up the resources and information system necessary to communicate disruptions and respond to them. The impact to production investment is that machines/tools must be predictable (maintainable to avoid breakdowns).

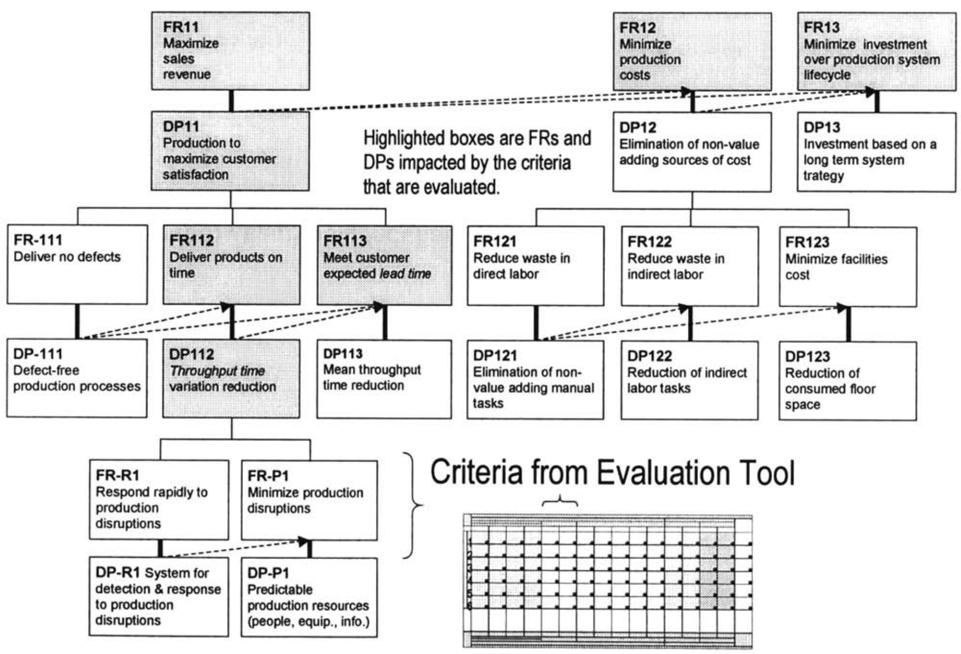

Figure 43: Interactions of throughput time variation

Mean Throughput Time ($\bar{x}$)

Figure 44 depicts how the criteria evaluated to reduce mean throughput time impact each other and the rest of the system. In eliminating run size delay *by DP-T1: Production of the* *desired mix and quantity during each demand interval*, reduces process to some extent because producing to the demand interval regulates the service rate of each part type so that it is not as erratic (very high, then low). *DP-T2 Production balanced to takt time* affects transportation delay because running to takt time is done with product flow oriented layouts that reduce the amount of transportation. *DP-T3 Reduction of transportation lot size* has interaction with transportation delay because large transportation lot sizes are used when transportation distances are great.

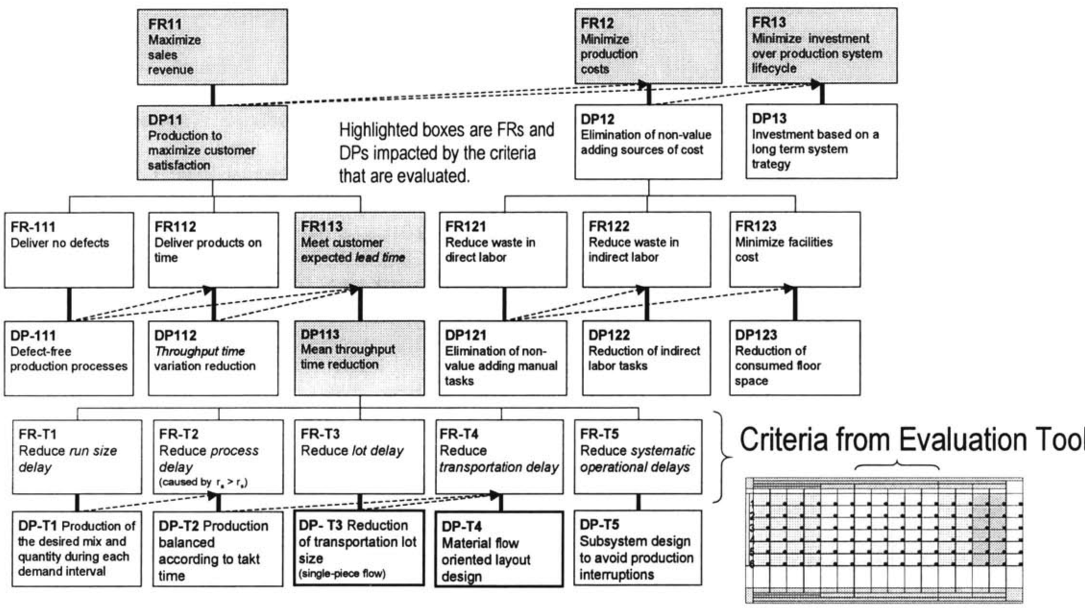

Figure 44: Interactions of mean throughput time (delay reduction)

The reduction of the five delays allows reduction in mean throughput time and increases customer satisfaction because they may receive their orders with a shorter lead time. The results of reducing throughput time also has strong impact on production cost and investment. By changing to flow oriented designs from a job shop environment for example may increase the total number of machines and decrease machine utilization. Minimizing production investment then, must be done by acquiring simpler machines that can accommodate changes in design and volume. Production cost must be addressed by separating workers from machines to avoid one operator per machine.

Direct Labor Cost

To minimize direct labor cost, the criteria of eliminating workers waiting on machines and wasted motion are evaluated as shown in Figure 45. However, as workers are separated from machines they must walk more, creating more wasted motion. The decomposition identifies this impact and so under elimination of wasted motion, the amount of walking between machines is assessed.

The elimination of non-value added manual tasks impacts indirect labor because with fewer tasks, there is less to manage and coordinate. The further impact on production investment emphasizes the requirements of autonomous machines, machines that may be configured to reduce walking distance, and ergonomic equipment.

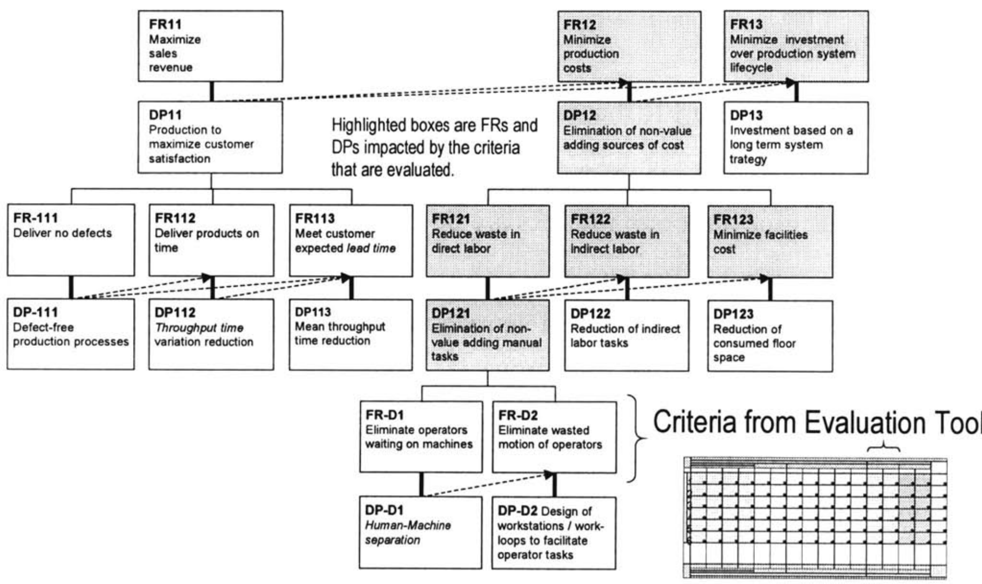

Figure 45: Interactions of direct labor

Indirect Labor Cost

The criteria evaluated in indirect labor cost are eliminating management tasks and information disruptions as shown in Figure 46. The impact on production investment comes from the design information system or visual management.

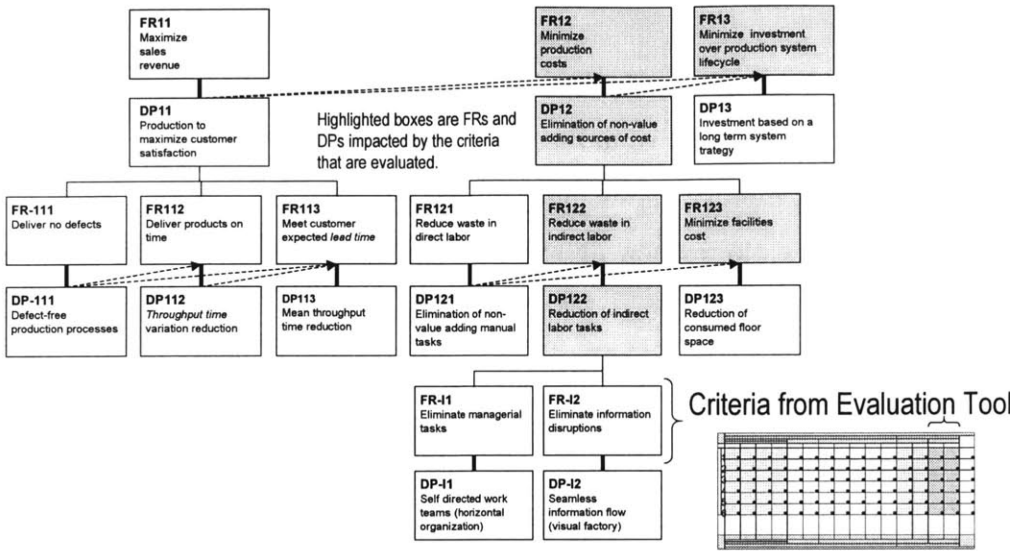

Figure 46: Interactions of indirect labor

Production Investment

As production investment is the FR that is most dependent on all the other considerations, a list of requirements for machines is presented. This is an example of physical integration of many DPs into one machine although the FRs are decoupled.

- Stable quality output (Stable Processes)
- Reliability and maintainability (Predictable resources)
- Quick changeover (run-size delay reduction)
- Cycle time ≤ minimum takt time (process delay reduction)
- Single piece processing (lot delay reduction)
- Self stopping, automatic error detection and shut off (Autonomation for man-machine separation – Eliminate workers waiting on machines)
- Reduced frontal area (eliminate wasted motion of operators)
- Flexibility (movable, upgradable)

8.4.3 Metrics

Although this chapter describes a qualitative method of evaluating a design, the functional requirements may also be assessed quantitatively using metrics as presented in Figure 47. In this figure, the metrics mirror the FRs so that there is one metric for each FR. Keeping track of these metrics may track the progress made when making changes to the production system and may motivate further improvements in the design.

Upper level PSD Decomposition (FRs/DPs)	FR: Maximize long term return on investment / DP: Manufacturing system design															
	FR: Maximize sales revenue / DP: Production to maximize customer satisfaction											FR: Minimize direct labor cost / DP: Elimination of non-value adding sources of cost				
	FR: Deliver no defects / DP: Defect free production				FR: Deliver products on time / DP: Throughput time variation reduction		FR: Meet customer expected lead time / DP: Mean throughput time reduction					FR: Reduce waste in direct labor / DP: Elimination of non-value adding manual tasks		FR: Reduce waste in indirect labor / DP: Reduction of indirect labor tasks		Minimize production investment
	FR: Stabilize Process / DP: Elimination of assignable causes of variation															
Evaluation Criteria (FRs)	Eliminate machine assignable causes	Eliminate operator assignable causes	Eliminate method assignable causes	Eliminate material assignable causes	Respond rapidly to production disruptions	Minimize production disruptions	Reduce run size delay	Reduce process delay	Reduce lot delay	Reduce transport delay	Reduce systematic operational delays	Eliminate operators waiting on machines	Eliminate wasted motion of operators	Eliminate managerial tasks	Eliminate information disruptions	

Metrics	# of non-conformances caused by machines	# of non-conformances caused by operators	# of non-conformances caused by method used	# of non-conformances caused by incoming parts	Average time required to eliminate root cause	# and time impact of production disruptions	Average run size	Cycle time / takt time of 1 for each station / system	Transfer lot size	Distance parts must travel through system	% of time down for routine tasks	% of time waiting on machine	% of time required for movement	% of employees in self directed work teams	% of system managed visually	% of value-added capital investment
	Process capability				% on-time delivery of parts / orders and variation of throughput time		Customer lead time and mean throughput time					% of value adding operator time		% of indirect employees		% of machines operating at or less than takt time
	Number of defects															
	Sales Revenue											Production Cost				
	Return on investment															

Figure 47: Metrics for each FR

8.5 Summary

Allowing production systems to evolve based on performance metrics leads to systems that are sub-optimal. In order to change the design of a system, adopting practices observed at other companies is not enough.

In this chapter, the development of an evaluation tool for assessing the design of a production system was presented. The contribution of this work is that it provides a method to analyze the interrelations of each element in the system using the axiomatic design approach. This analysis introduces the possible use of the information axiom [Suh, 1990] to evaluate a production system design. Further research is required to actually quantify the assessment by calculating the information content (equation 3) of a production system design.

The application of this tool may be to assess project proposals, measure and document progress in production system design and guide the design of the system.

Chapter 9: Conclusions

9.1 From Wing Assembly Case Study

In comparing the wing assembly sites from the data collected, little insight into differences in the system characteristics or performances was gained, due to the variation in product design and program maturity. However, the observations and data were used to characterize the industry and identify opportunities for improvement.

The PSD decomposition was used as a framework for analysis of the wing assembly systems. This analysis was useful in highlighting potential improvements in the system design and the different implications that Lean principles have in the aircraft industry. Comparisons made within individual sites also supported the relationships between quality, operator work, throughput time and cost as identified by the PSD decomposition. Further refinement of this decomposition may continue to provide insight into the design of Lean production systems in the aircraft industry.

9.1.1 Quality – Stable Processes

In airframe assembly, achieving stable processes is the greatest challenge. It was also observed to have a significant impact on cost, throughput time and was identified as the greatest source of production disruption.

The challenge in achieving stable processes arises from producing an assembly with tight tolerances from parts with high dimensional variation. Problems such as the compliance of the large parts, thermal expansion, tolerance stack-ups and aggressive product design aggravate the situation. In airframe assembly, to stabilize the process, the craftsmanship involved in dealing with these problems must be standardized (along with advances in product design through DFA and DFM).

Non-conformance costs (labor plus overhead) were large (15-35%) compared with the total labor cost of assembling a wing. In proportion, 4 – 17 % of total labor hours were spent on rework and repair. Rework and repair hours also showed a correlation with total labor hours and throughput time. Data from one site showed that for every hour of rework performed, the total labor hours increased by 1.2 hours. The throughput time also increased by 5% for every 100 hours of rework. Although final product quality was very high, the amount of effort in inspection and redoing work is enormous. The quality issues observed caused unpredictable delays, which causes throughput time variation and thus an increase in the mean throughput time.

As airframe assembly involves high amounts of manual assembly, the stability of operator work output must be addressed. Standardization in the aircraft industry has a different character compared to the automotive industry. Because each part may require custom fitting, describing each step in assembly is not possible. It is usually up to the expertise of the operator to trim, shim and fixture the parts so that they fit together properly. However, experienced operators usually have special methods to assemble the parts so that they fit together properly and cause minimal downstream problems. These are the methods that must be captured, standardized and passed on through formal training.

Part of standardization is to improve the work instructions so that they reflect not only *what* has to be done, but also *how* to perform the tasks with a system in place so that new practices or better methods may be incorporated easily. It is important that the operators have strong input into these work instructions so that their methods may be documented.

At all the sites, the formal training programs certified operators in the skills they would need. However, there were no systematic methods for on the job training, which was usually done by observing other workers or asking for assistance when required. As many tasks have special methods, they should be taught by workers who are knowledgeable of the tasks and trained in teaching them as well.

Once standardized methods are in place and sustained through the training program, the remaining common operator errors may be reduced by mistake proofing those operations. Humans will inevitably make errors and to ensure quality, the errors must be decoupled from the act of producing a defect or quality issue. These methods often referred to as poka-yoke may be as simple as the current usage of drilling fixtures and should be expanded upon. The order of these implementations are important because standard work has to be established before it can be passed along by training, and mistake proofing operations would be a daunting task unless variability in operator output is first reduced.

9.1.2 Throughput Time Variation

Throughput time variation exists when tasks at a work center may take shorter or longer to complete depending on the occurrence of unpredictable production disruptions. The production disruptions observed and reported were due to quality, part shortages, waiting for inspection, waiting for engineering, design changes, people availability and machine/tool availability. The relative frequency and impact of each type of disruption varied among the different sites but quality (non-conformances) was the most consistently reported disruption.

Although these production disruptions occurred frequently, their impact was hidden, as the planning is conservative enough for these disruptions to occur without greatly impacting the schedule. In most cases overtime – high levels observed (13 – 25%) – was also used to alleviate the impact of production disruptions.

Developing a system to eliminate common cause production disruptions (people, tools, waiting for inspection, machines down) may reduce these time variations. So far, it has been observed that this approach has been limited to quality issues (corrective action system) and in some cases, parts supply. However, any resource that may cause a production disruption should be identified and eliminated. Most systems did not capture the reasons for delays and their impact (although some sites subsequently implemented the capture of this data). Along with identifying these disruptions there must be a procedure to prevent their reoccurrence. Along with this type of detection and response system, all of the resources must be designed to be predictable; perfect attendance, cross training, maintenance of equipment, and pull systems for parts supply may be implemented to ensure predictability of resources.

Reducing the occurrence of production disruptions will ensure delivery on time with decreases in throughput time and reduced production cost.

9.1.3 Mean Throughput Time

Studying actual/planned throughput times in airframe assembly did not yield a significant contrast. All sites were able to meet their planned throughput time to a similar degree because the manufacturing lead-times were set to allow delivery on time with the expected amount of production disruptions. This made actual/planned throughput time a poor comparison metric in this case.

Reducing quality problems and time variation will allow significant reductions in manufacturing lead-time (planned throughput time) as shown in Figure 48. Theoretically, the manufacturing lead times are set based on a probability level of delivering on time from the probability density graph. In practice, manufacturing lead-time is set based on actual throughput time and adding some fudge factor [Spearman and Hopp, 1990] to account for the production disruptions. By reducing the time variation, the manufacturing lead times of sub-systems may be reduced with the same level of delivery performance, having a significant impact on the overall throughput time.

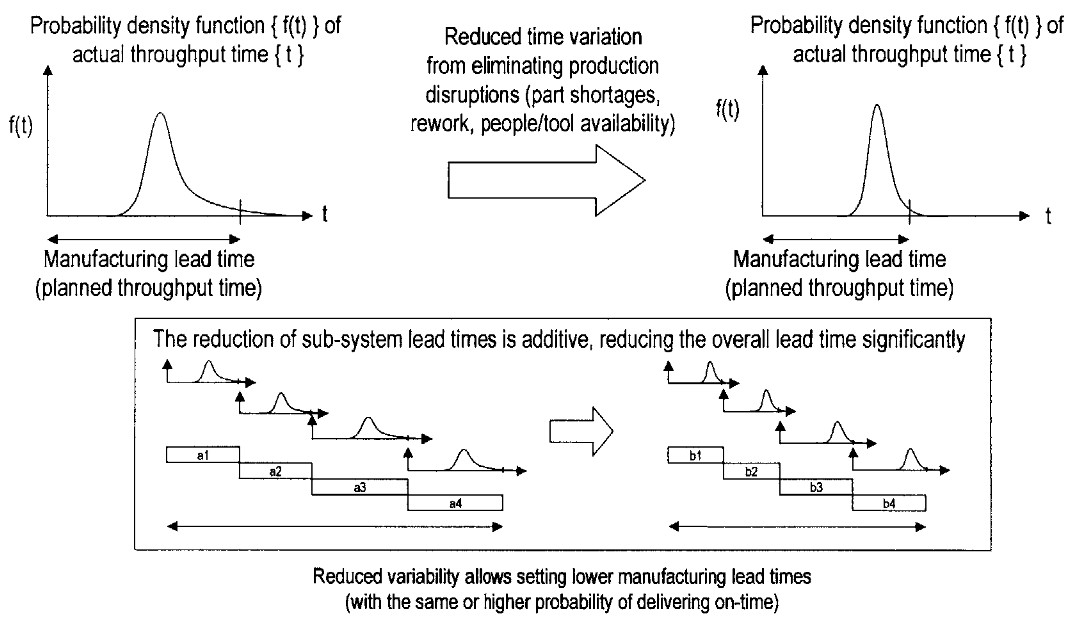

Figure 48: Impact of variation on manufacturing lead-time (planned throughput time)

Eliminating non-value-added tasks in the process may further reduce throughput time as well. These tasks may include inspection and work preparation. Operators were also observed to have to walk long distances to replace supplies such as drill bits, sealant and other miscellaneous supplies. By implementing self-inspection and having all resources for the operator delivered to the point of use (kits) the throughput time of each work package may be decreased as investigated in the B-2 case study.

9.1.4 Production Cost – Direct Labor

One of the problems in trying to reduce production costs is the habit of tracking and minimizing direct labor hours. By doing so, when production disruptions occur, managers keep workers busy by doing work out of sequence or even starting the next assembly. These practices add variation to the process but more importantly, they hide the impact of the production disruptions. By constantly working around the disruptions, the problems eventually become acceptable.

Production cost reduction may be dramatically impacted by the implementations discussed in quality, time variation and mean throughput time. Hopefully, this will drive the focus of production management away from tracking direct labor cost to focus on these issues.

Another practice impacting production cost was that of sending incomplete wings to final assembly accompanied with workers to complete the tasks out-of-station. To study the impact of this practice, the amount of out of station work was compared with total labor cost. There was a significantly strong correlation between these factors at the site where this was analyzed, and for every hour of out of station work done, the total labor cost increased by 0.8 hours. This result suggests that an hour of work requires 1.8 hours to complete out of station. Out of station work was also reported to impact quality, interfere with the work in final assembly and deprive workers from their regular stations. These impacts were not quantifiable with the available data though.

9.1.5 Production Cost – Indirect Labor

Excess indirect labor is required for management tasks and to deal with information disruptions. Common management tasks are to eliminate the impact of production disruptions to keep workers and production going. By eliminating the production disruptions and organizing self directed work teams, the amount of management tasks may be reduced.

One of the observations made was the existence the informal systems in place to supplement the MRP system. These were the expediting and recovery schedule practices. To minimize the impact of part shortages on assembly, there were often teams of production control personnel dedicated to identifying the parts that would impact assembly and then expediting them. When production fell behind schedule, recovery schedules were used to drive the system back on schedule. However, this was done independently of the MRP schedule, which drove the parts requirements. Ultimately, fabrication centers had long lists of late parts and did not know which ones were really of need without the constant expediting system. The solution to this problem cannot be to adhere more closely with the MRP schedule. Its use as a planning tool may be indispensable but to actually control production, simpler information systems should be put in place (pull systems as an example) so that fabrication centers and suppliers know the actual needs of assembly. Hopefully, this would also reduce the costs in expediting and circumventing the current system.

9.1.6 Production Investment

Designing equipment to function well in the system should be considered. By dividing the complex automated drilling machines into a number of simpler machines which perform fewer functions may impact flow, reliability, flexibility the ability to upgrade more easily and the ability to form cells.

It was also observed in military programs that the procurement policies impact the program life-cycle investment costs. By acquiring all the tooling up-front, resources are wasted if the production rate does not reach expected levels (if the demand is changed). As well, by adding tooling incrementally, improvements or resolution of problems may be incorporated into the next set of tooling. Costs are also reduced in this case if the time value of money is considered. This issue should be addressed by altering the procurement policies to promote the acquisition of investment incrementally.

9.2 From B-2 Case Study

By providing kits and prepared materials to the operators, the preparation tasks were not eliminated but decoupled from the technician. Instead of the technician interrupting their tasks for material handling and preparation tasks, another worker does them in parallel so that the value-added tasks are continuous. However, the amount of walking away from the stations was isolated to the material handler and all the materials necessary were centralized for them. The methods and special tools developed by experienced operators were used to standardize the tasks, capturing the best shop floor practices. Further improvements in ergonomics and work instructions were also applied. These Lean implementation projects showed significant decreases in the amount of rework (52% decrease), overtime (24% decrease) and total labor hours (21% decrease compared to expected reductions). The throughput time variation decreased as well.

9.3 From Analysis of Military Aircraft Procurement Policies

The focus on high performance in design and continual engineering changes makes establishing stable production processes very difficult. It creates products that are inherently difficult to build and then confounds efforts towards standardization, an already difficult task in airframe assembly. As the customer focuses more attention on the production as opposed to just the product performance, manufacturing issues may gain influence in the design and development process.

To ensure that the production cost is less than the negotiated cost within the contract lot, manufacturers have incentive to take conservative, short-term approaches to cost reduction. Parts and materials are acquired far in advance so they are posted as actual costs prior to negotiation, reducing the risk of unexpected price increases. Incentives allowing manufacturers to keep a portion of the profits from extra cost reductions and longer contracts [Harris, 1999] may alleviate these problems.

By paying for all of the investment up-front, the government creates incentive for acquisition of tooling before required and motivates the minimization of up-front investment cost. As the assets are also paid for, there is no incentive to reduce the level of inventory. This policy must be carefully designed to promote reduction in the long-term investment cost by acquiring equipment incrementally and with flexibility to accommodate the potential changes in design and production rate.

9.4 From PSD Evaluation

Allowing production systems to evolve based on performance metrics leads to systems that are sub-optimal. In order to change the design of a system, adopting practices observed at other companies is not enough.

The development of an evaluation tool for assessing the design of a production system was presented. The contribution of this work is that it provides a method to analyze the interrelations of each element in the system using the axiomatic design approach.

The application of this tool may be to assess project proposals, measure and document progress in production system design and guide the design of the system to improve the performance of the entire production system.

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Appendix A – LAI Research Plan

Title: Design and Management of Complex Manufacturing Systems

Motivation

Each consortium member wishes to learn how to convert a production system founded with a craft mentality to a lean production system. The researchers have been able to administer surveys and questionnaires but this has not provided the level of detail to reveal implementation issues. This project is designed to delve more deeply into member and non-member companies to understand how to design and manage lean manufacturing systems.

Key Questions

The key questions for this research as defined by the focus team were:

- What are the enabling practices in overarching practice number one of the Lean Enterprise Model (LEM), "flow optimization," that allows factory operations to reduce the cycle time to produce a product?
- What are the interactions with the other overarching practices of the LEM that are important in reducing cycle time to produce a product?

Research Design

The research was field research at participating initiative member sites. Each site resulted in a separate case study. Multiple sites were necessary to generalize results. In the course of conducting and defining this research, several additional research projects have been spawned: Lean Assembly System Design, and Production Variance Estimation and Reduction. These projects are described separately. This project has developed into a study of the performance of the manufacturing system using the key metrics of planned assembly time, actual assembly time, reasons for delay and information about system characteristics.

Through a disciplined approach to data collection the major contributors to perturbations in the manufacturing systems were explored for lessons on lean system design.

Staffing

The research was conducted by the Factory Operations Research Team at MIT. Students participating with this team were involved in this research. A student was assigned to prepare the case study for each site investigated. This case study or a combination of case studies will entail a thesis project. Luis Ramirez was responsible for the thesis project on the engine sector and Andrew Wang conducted the research in the airframe sector. Additional students will be assigned the remaining sectors (Electronics and Space). The thesis advisors were members of the research team (Tim Gutowski, Stan Gershwin, or Dave Cochran) and Tom Shields will be the designated thesis reader.

Timetable

This research is being accomplished during the three years of Phase II of the LAI. It was anticipated that it would take about nine months per sector. Additional time may be allocated to monitor experiments that are accepted by the case study site. As the research team gets more proficient at doing this research it is anticipated that multiple sites may be investigated at once. The engine sector study has been completed and the airframe field research has been completed. Airframe sector results have been reported at the fall Plenary Focus Team Meeting. The electronics sector research will commence during year three of Phase II.

Expected Products

Preliminary reports will be issued after each sector has been studied. The engine sector final report is awaiting approval from investigated sites. It is anticipated that one or more theses will be produced during this effort. Each of the reports will support updates and additions to the LEM. Since the focus of the study is on cycle time reductions, it is anticipated that new and improved practices will be developed to support this objective.

Appendix B – Sample Hypothesis Testing Equations[18]

Testing for a difference in mean between two samples

Null Hypothesis: There is no difference in the means of the two populations (μ_1-μ_2 = 0)

Alternative hypothesis: There is a difference in the means of the two populations (μ_1-$\mu_2 \neq 0$)

A significance level of p=0.05 is chosen (95% confidence)

Now, calculate mean and standard deviation of the two samples, M_1, M_2, S_1, S_2 that have sample sizes of n_1 and n_2 respectively.

Using a t-test, calculate t:

$$t = \frac{M_1 - M_2}{\text{Standard Error}}$$

Standard Error: $S_{Md} = \sqrt{\frac{S_1^{\,2}}{n_1} + \frac{S_2^{\,2}}{n_2}}$

$$t = \frac{M_1 - M_2}{\sqrt{\frac{S_1^{\,2}}{n_1} + \frac{S_2^{\,2}}{n_2}}}$$

Using the t value for a 1-tailed test, and $n_1 + n_2 - 2$ degrees of freedom, the value of p is determined from the t-distribution.

If $p \leq 0.05$, then the null hypothesis may be rejected with 95% confidence.

[18] Material summarized from Stockburger [1996].

Testing for correlation of data (Using Pearson's correlation)

Null Hypothesis: There is no correlation between the two measures (cost, quality, throughput time etc.) in the population ($\rho = 0$)

Alternative hypothesis: There is a correlation between the two measures in the population ($\rho \neq 0$).

A significance level of p=0.05 is chosen (95% confidence)

Next calculate the sample value of Pearson's correlation (r)

$$r = \frac{\sum XY - \frac{\sum X \sum Y}{N}}{\sqrt{\left(\sum X^2 - \frac{(\sum X)^2}{N}\right)\left(\sum Y^2 - \frac{(\sum Y)^2}{N}\right)}}$$

Then, the probability that this r value is not the value in the null hypothesis must be determined using the formula,

$t = \frac{r}{s_r}$, where s_r is the standard error calculated by, $s_r = \sqrt{\frac{1-r^2}{N-2}}$

Knowing the t value and the degrees of freedom (N-2), a t table can be used to find the probability p. (One tail test if the data shows a strong slope, otherwise two tail test is used.)

If $p \leq 0.05$, then the null hypothesis may be rejected with 95% confidence and the correlation is significant.

Appendix C – Design of Delay Questionnaire

For each of the identified delay categories, the frequency of occurrence was assessed on a scale of 1 to 5 and then the impact was also assessed on a scale of 1 to 5. Crewmembers, crew chiefs, the foreman, and inspector were interviewed for a total of 13 interviews at one site, and 7 at another. The results were tallied and for each category, the frequency was multiplied by the impact to assess the relative time impact of each delay category. The following is the list of delay categories used in the interviews, with an explanation for each one.

Waiting for Engineering Disposition - A quality issue has been detected and work cannot continue until the engineering disposition returns. (The longest delays are when engineering has to send out for strength analysis, which may take many days)

Engineering Disposition call delay - Work cannot continue due to waiting for a quality issue to be looked at so that the problem may be written up for analysis.

Part Shortages - Work cannot continue because the parts are unavailable.

Rework - A delay occurs because dispositions are being reworked.

Waiting for Inspection - Work is finished and waiting for inspector to check off.

People unavailable – Not enough workers or workers with the required experience are available to perform a job.

Conducting OJT – Workers are unavailable because they are training other workers.

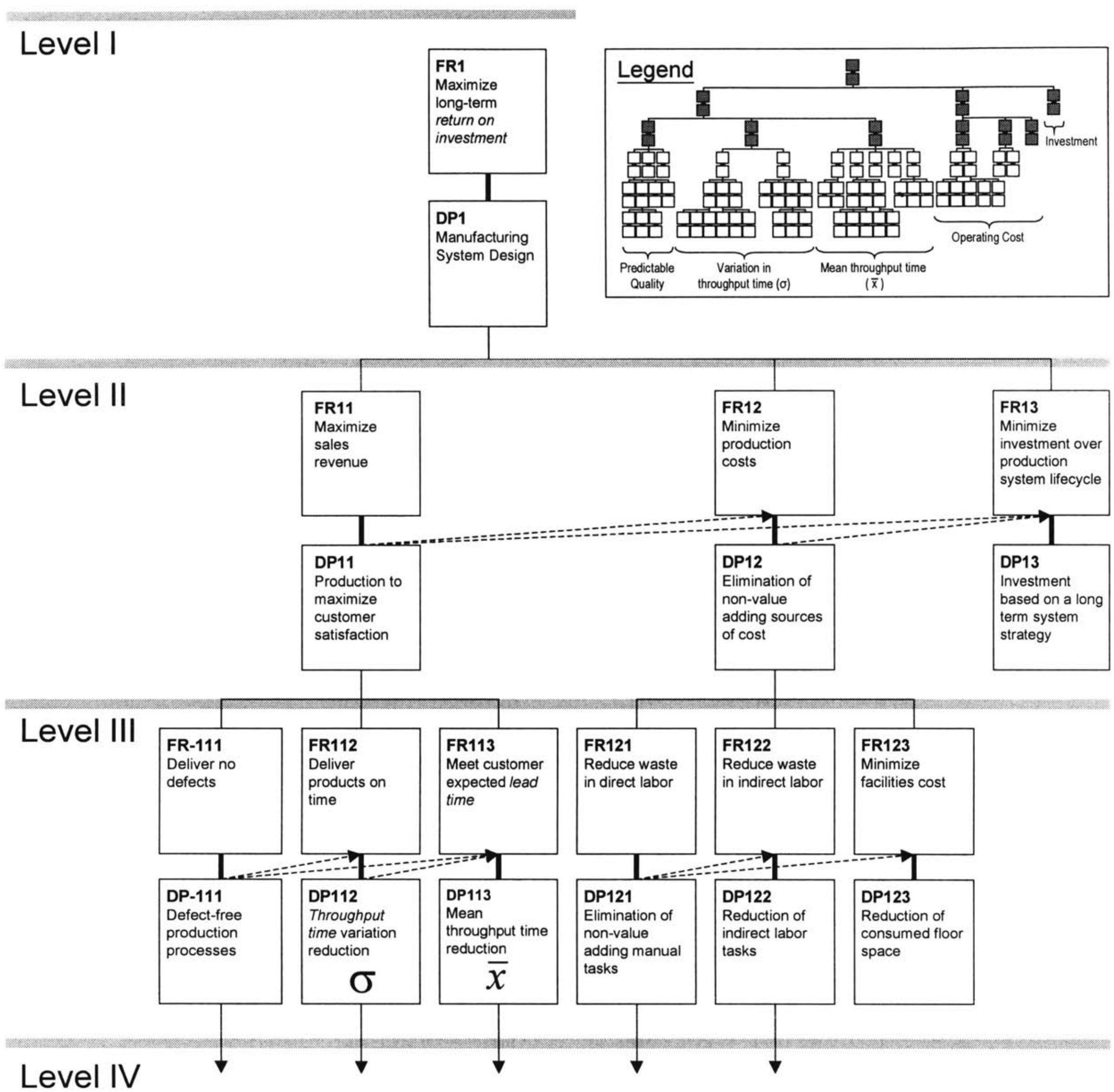
Out of station work – Work cannot be done because workers are working on jobs out of the station or because other workers finishing up from other stations are in the way.

Compensating for tolerance stack-ups – Tasks such as trimming, shimming due to gaps or interference.

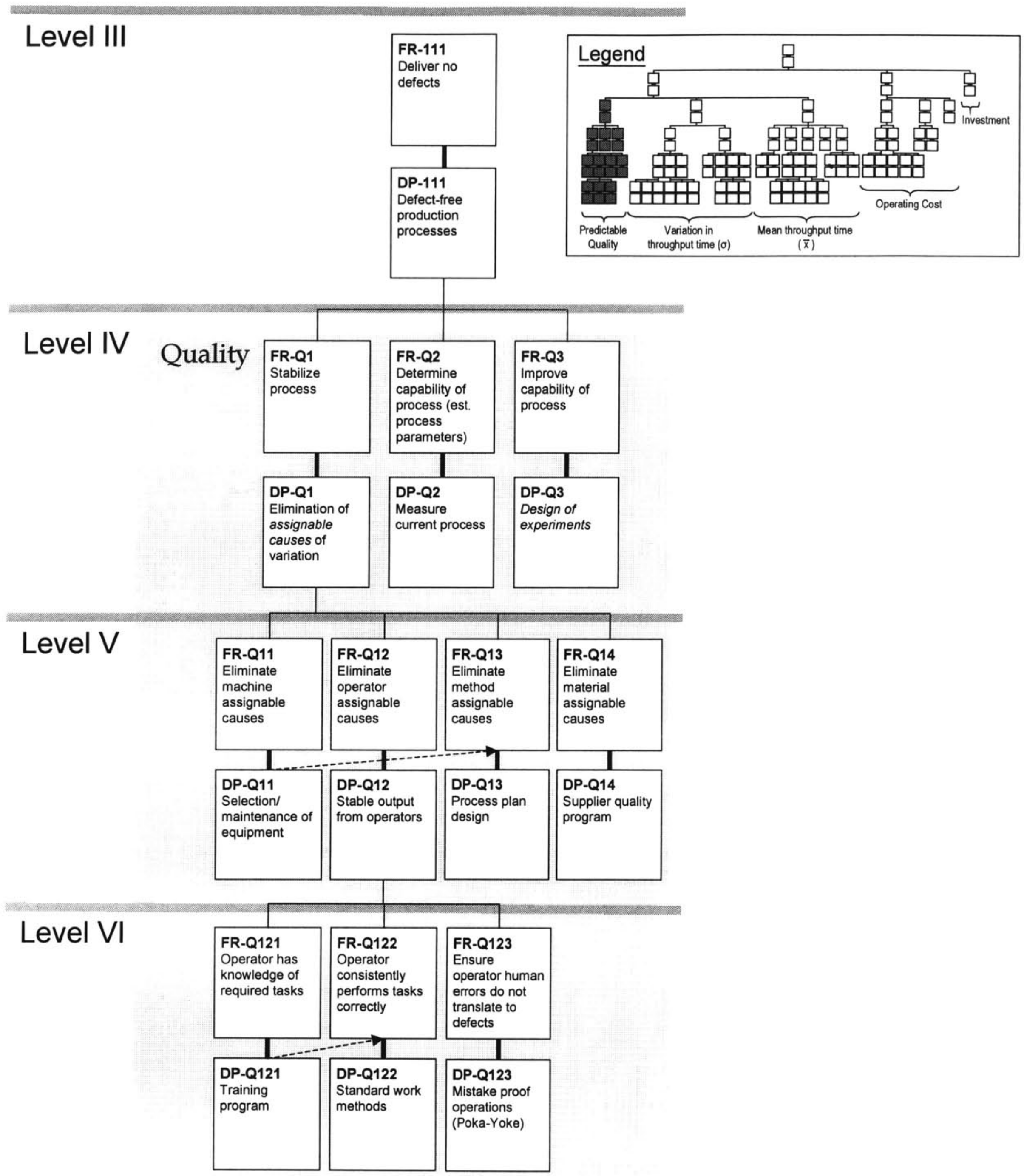
Waiting for Tools/Jigs – An assembly cannot be worked on because a tool or jig is already occupied.

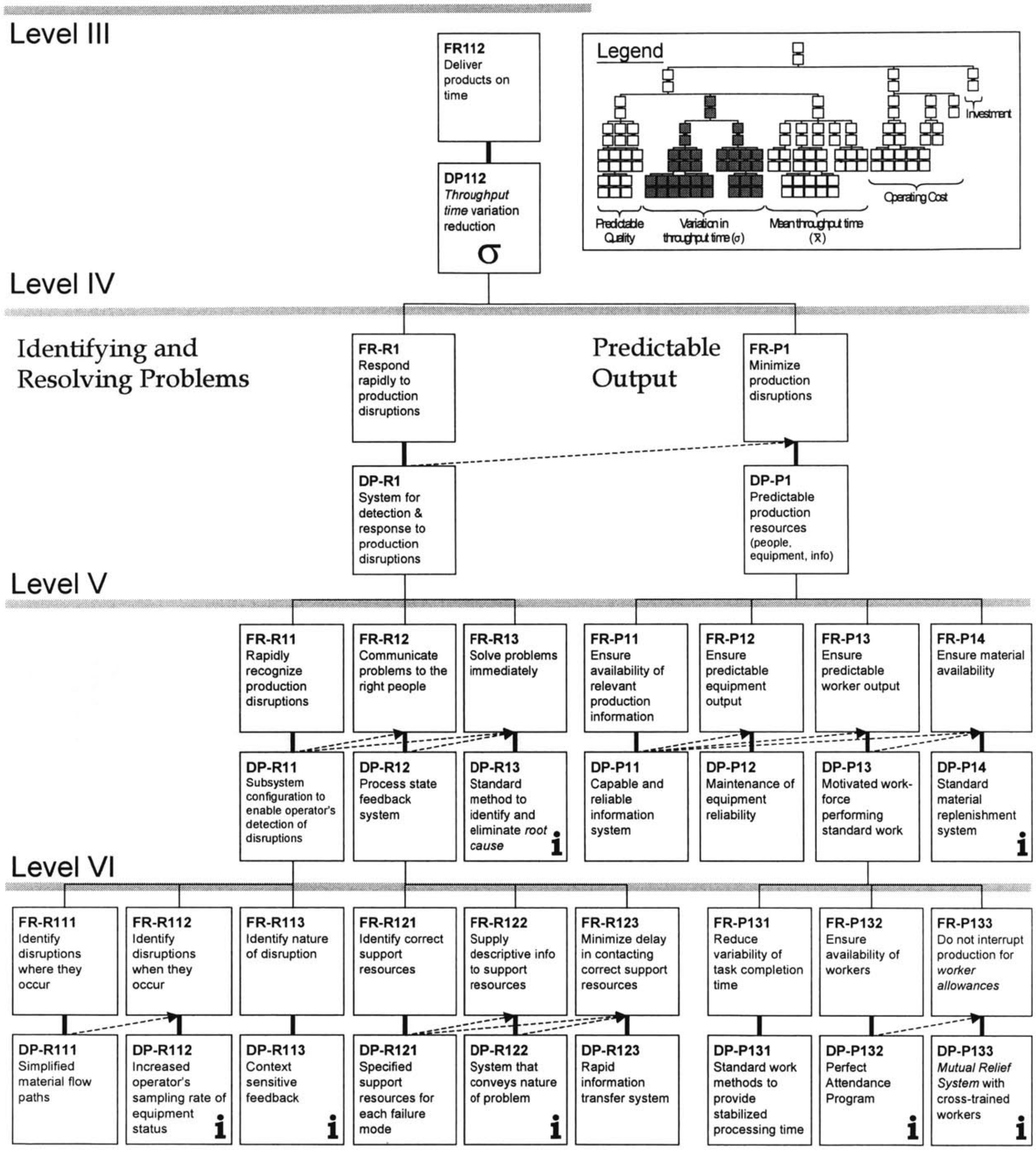
Appendix D – PSD Decomposition[19]

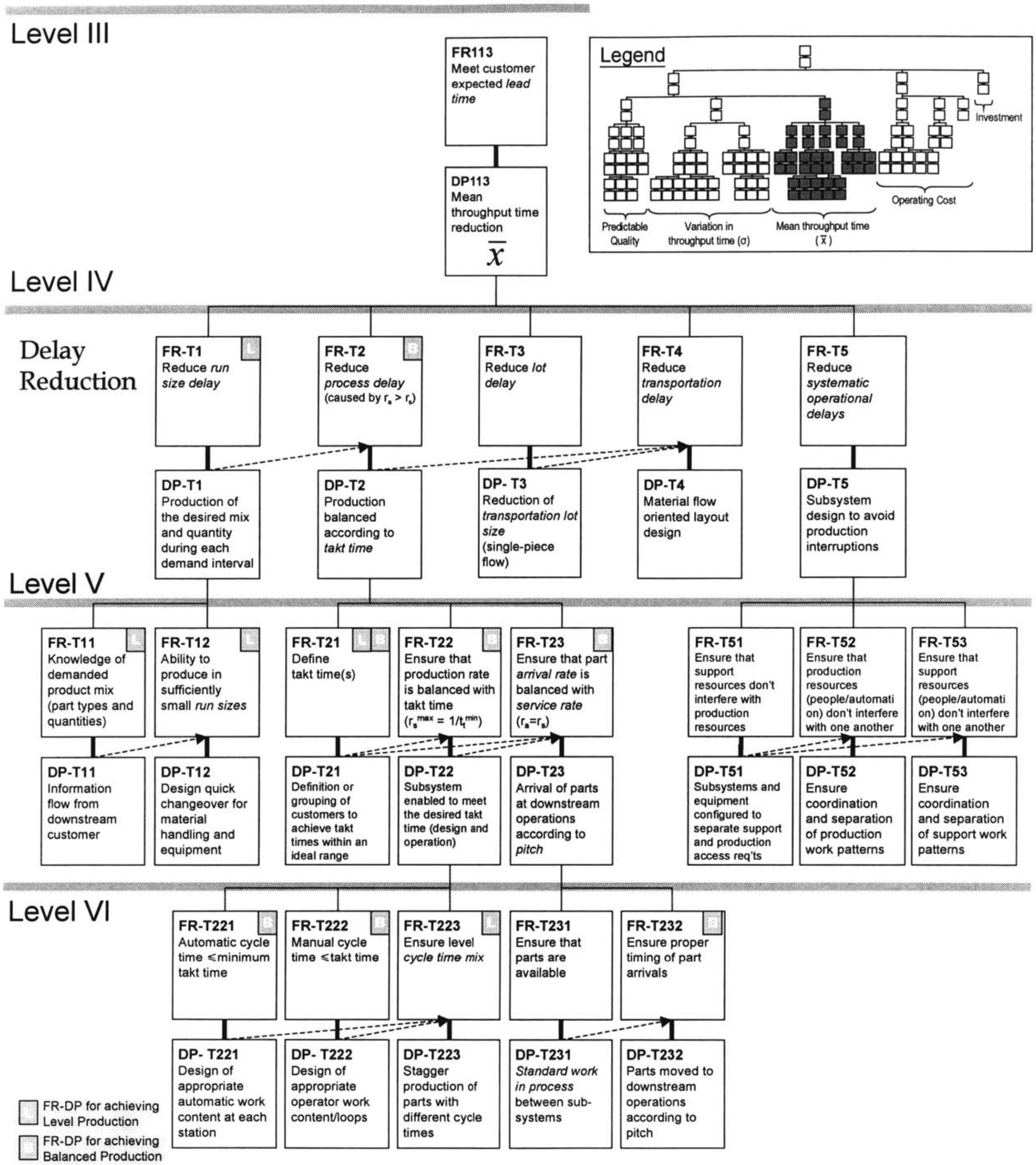
The PSD decomposition chart is presented here divided among 5 pages. Each page has a legend with highlighted boxes indicating the section represented on the page.

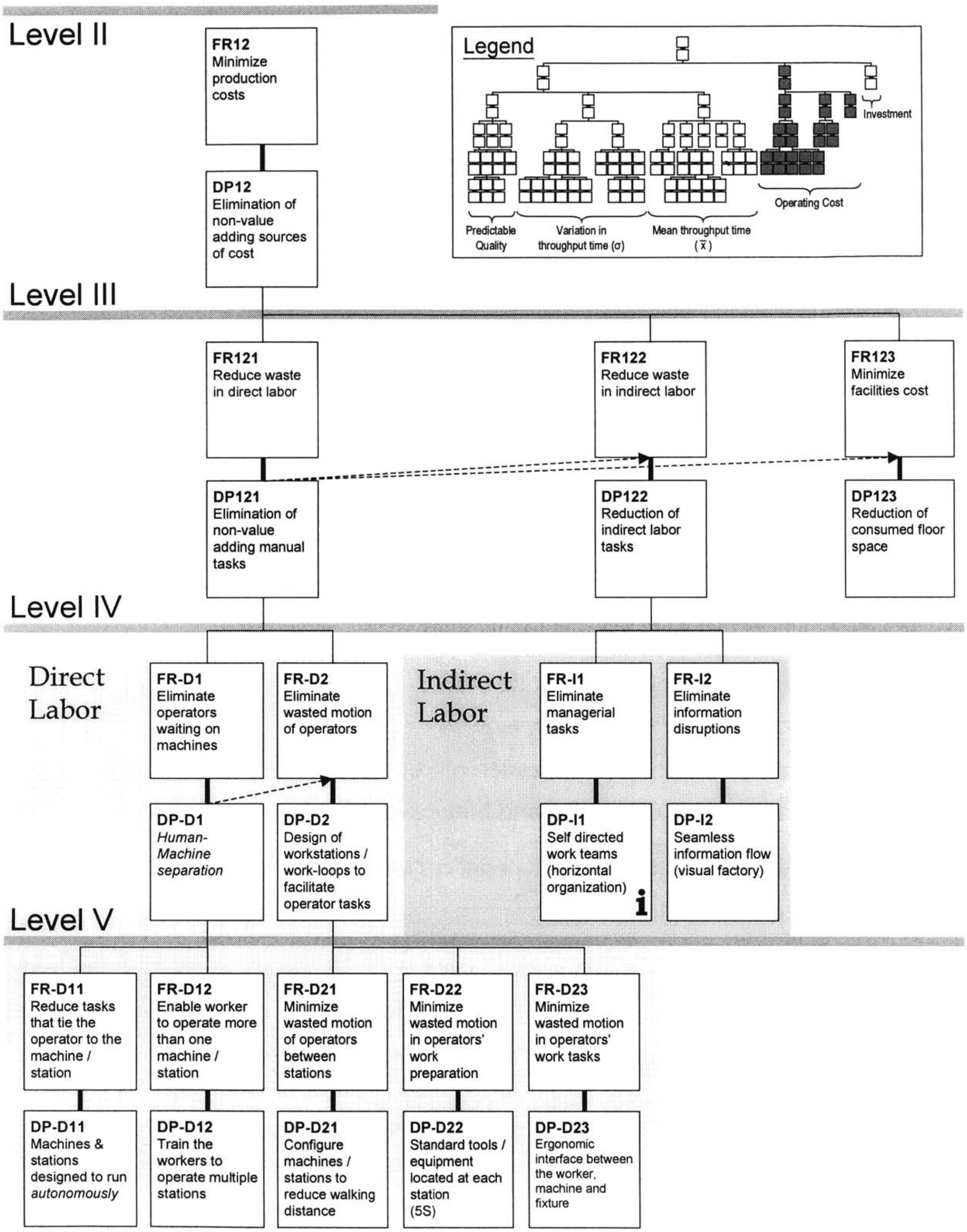


[19] PSD decomposition v5.0 by Prof. David Cochran, Jorge Arinez, Staffan Bröte, Micah Collins, Daniel Dobbs, Jim Duda, Yong Suk Kim, Kristina Kuest, Jochen Linck, Jose Castaneda-Vega and Andrew Wang. As this is an ongoing work, the most current version of this work may be obtained by contacting Prof. Cochran.


Level III
FR-111 Deliver no defects
DP-111 Defect-free production processes
Legend
Investment
Operating Cost
Predictable Quality
Variation in throughput time (σ)
Mean throughput time (x̄)
Level IV
Quality
FR-Q1 Stabilize process
FR-Q2 Determine capability of process (est. process parameters)
FR-Q3 Improve capability of process
DP-Q1 Elimination of *assignable causes* of variation
DP-Q2 Measure current process
DP-Q3 *Design of experiments*
Level V
FR-Q11 Eliminate machine assignable causes
FR-Q12 Eliminate operator assignable causes
FR-Q13 Eliminate method assignable causes
FR-Q14 Eliminate material assignable causes
DP-Q11 Selection/ maintenance of equipment
DP-Q12 Stable output from operators
DP-Q13 Process plan design
DP-Q14 Supplier quality program
Level VI
FR-Q121 Operator has knowledge of required tasks
FR-Q122 Operator consistently performs tasks correctly
FR-Q123 Ensure operator human errors do not translate to defects
DP-Q121 Training program
DP-Q122 Standard work methods
DP-Q123 Mistake proof operations (Poka-Yoke)


Level III
FR112 Deliver products on time
DP112 *Throughput time* variation reduction σ
Legend
Investment
Operating Cost
Predictable Quality
Variation in throughput time (σ)
Mean throughput time (X̄)
Level IV
Identifying and Resolving Problems
Predictable Output
FR-R1 Respond rapidly to production disruptions
FR-P1 Minimize production disruptions
DP-R1 System for detection & response to production disruptions
DP-P1 Predictable production resources (people, equipment, info)
Level V
FR-R11 Rapidly recognize production disruptions
FR-R12 Communicate problems to the right people
FR-R13 Solve problems immediately
FR-P11 Ensure availability of relevant production information
FR-P12 Ensure predictable equipment output
FR-P13 Ensure predictable worker output
FR-P14 Ensure material availability
DP-R11 Subsystem configuration to enable operator's detection of disruptions
DP-R12 Process state feedback system
DP-R13 Standard method to identify and eliminate *root cause*
DP-P11 Capable and reliable information system
DP-P12 Maintenance of equipment reliability
DP-P13 Motivated work-force performing standard work
DP-P14 Standard material replenishment system
Level VI
FR-R111 Identify disruptions where they occur
FR-R112 Identify disruptions when they occur
FR-R113 Identify nature of disruption
FR-R121 Identify correct support resources
FR-R122 Supply descriptive info to support resources
FR-R123 Minimize delay in contacting correct support resources
FR-P131 Reduce variability of task completion time
FR-P132 Ensure availability of workers
FR-P133 Do not interrupt production for *worker allowances*
DP-R111 Simplified material flow paths
DP-R112 Increased operator's sampling rate of equipment status
DP-R113 Context sensitive feedback
DP-R121 Specified support resources for each failure mode
DP-R122 System that conveys nature of problem
DP-R123 Rapid information transfer system
DP-P131 Standard work methods to provide stabilized processing time
DP-P132 Perfect Attendance Program
DP-P133 *Mutual Relief System* with cross-trained workers


Level III
FR113 Meet customer expected lead time
DP113 Mean throughput time reduction $\overline{x}$
Legend
Investment
Operating Cost
Predictable Quality
Variation in throughput time (σ)
Mean throughput time ($\overline{x}$)
Level IV
Delay Reduction
FR-T1 Reduce run size delay
FR-T2 Reduce process delay (caused by $r_a > r_s$)
FR-T3 Reduce lot delay
FR-T4 Reduce transportation delay
FR-T5 Reduce systematic operational delays
DP-T1 Production of the desired mix and quantity during each demand interval
DP-T2 Production balanced according to takt time
DP- T3 Reduction of transportation lot size (single-piece flow)
DP-T4 Material flow oriented layout design
DP-T5 Subsystem design to avoid production interruptions
Level V
FR-T11 Knowledge of demanded product mix (part types and quantities)
FR-T12 Ability to produce in sufficiently small run sizes
FR-T21 Define takt time(s)
FR-T22 Ensure that production rate is balanced with takt time ($r_s^{max} = 1/t_t^{min}$)
FR-T23 Ensure that part arrival rate is balanced with service rate ($r_a = r_s$)
FR-T51 Ensure that support resources don't interfere with production resources
FR-T52 Ensure that production resources (people/automation) don't interfere with one another
FR-T53 Ensure that support resources (people/automation) don't interfere with one another
DP-T11 Information flow from downstream customer
DP-T12 Design quick changeover for material handling and equipment
DP-T21 Definition or grouping of customers to achieve takt times within an ideal range
DP-T22 Subsystem enabled to meet the desired takt time (design and operation)
DP-T23 Arrival of parts at downstream operations according to pitch
DP-T51 Subsystems and equipment configured to separate support and production access req'ts
DP-T52 Ensure coordination and separation of production work patterns
DP-T53 Ensure coordination and separation of support work patterns
Level VI
FR-T221 Automatic cycle time ≤minimum takt time
FR-T222 Manual cycle time ≤takt time
FR-T223 Ensure level cycle time mix
FR-T231 Ensure that parts are available
FR-T232 Ensure proper timing of part arrivals
DP- T221 Design of appropriate automatic work content at each station
DP- T222 Design of appropriate operator work content/loops
DP-T223 Stagger production of parts with different cycle times
DP-T231 Standard work in process between sub-systems
DP-T232 Parts moved to downstream operations according to pitch
FR-DP for achieving Level Production
FR-DP for achieving Balanced Production


Level II
FR12 Minimize production costs
DP12 Elimination of non-value adding sources of cost
Legend
Investment
Operating Cost
Predictable Quality
Variation in throughput time (σ)
Mean throughput time (x̄)
Level III
FR121 Reduce waste in direct labor
FR122 Reduce waste in indirect labor
FR123 Minimize facilities cost
DP121 Elimination of non-value adding manual tasks
DP122 Reduction of indirect labor tasks
DP123 Reduction of consumed floor space
Level IV
Direct Labor
FR-D1 Eliminate operators waiting on machines
FR-D2 Eliminate wasted motion of operators
Indirect Labor
FR-I1 Eliminate managerial tasks
FR-I2 Eliminate information disruptions
DP-D1 Human-Machine separation
DP-D2 Design of workstations / work-loops to facilitate operator tasks
DP-I1 Self directed work teams (horizontal organization)
i
DP-I2 Seamless information flow (visual factory)
Level V
FR-D11 Reduce tasks that tie the operator to the machine / station
FR-D12 Enable worker to operate more than one machine / station
FR-D21 Minimize wasted motion of operators between stations
FR-D22 Minimize wasted motion in operators' work preparation
FR-D23 Minimize wasted motion in operators' work tasks
DP-D11 Machines & stations designed to run autonomously
DP-D12 Train the workers to operate multiple stations
DP-D21 Configure machines / stations to reduce walking distance
DP-D22 Standard tools / equipment located at each station (5S)
DP-D23 Ergonomic interface between the worker, machine and fixture

Appendix E – LEM Observations at the B-2 LO Process

The framework used by LAI to organize its research activities and to describe lean enterprise principles and practices is the Lean Enterprise Model. The following analysis presents whether the Enabling Practices prescribed by this model were observed at the site studied. This analysis is used to identify opportunities for enterprises to make improvements towards creating a "Lean Enterprise". In addition, the results from this analysis may be used in the future to determine the impact of each Enabling Practice on the performance of the enterprise.

Observations were made mainly on the Low Observable Process. The LEM is organized into 12 Overarching Practices, each of which is supported by Enabling Practices. The Overarching Practices that were relevant to this study were:

OAP 1 – Identify and Optimize Enterprise Flow
OAP 2 – Assure Seamless Information Flow
OAP 3 – Optimize Capability and Utilization of People
OAP 11 – Ensure Process Capability and Maturation

Table 8 lists the relevant Enabling Practices under each Overarching Practice, and whether they were observed to be implemented.

It must be noted that the observations presented here are highly subjective and lacks consistent criteria for determining whether each enabling practice was implemented. These are the observations from the site visit and are listed as a reference only. It is recommended that more structured criteria for using the LEM are developed.

Table 8: LEM Observations at the B-2 LO process[20]

OAP 1 – Identify and Optimize Enterprise Flow

		Explanation
Establish models and/or simulations to permit understanding and evaluation of the flow process	Yes	Operators are videotaped and their operations and material flow are observed and improved.
Reduce the number of flow paths	Yes	Implementation of part kits has eliminated need for technician to leave plane for multiple items. Material handler brings parts to technician.
Minimize inventory through all tiers of the value chain	Yes	Eliminating large central parts cribs. Have standard, controlled part cribs at the plane.
Reduce setup times	Yes	Kitting and work preparation done separately from touch work.
Implement process owner inspection throughout the value chain	Partially	Working to develop self-accountability in work force so that they inspect their own work.
Strive for single piece flow	Partially	Work packages help coordinate work.
Minimize space utilized and distance traveled by personnel and material	Yes	Use of kits and material handlers doing preparation work decreases total amount of travel required.
Synchronize production and delivery throughout the value chain	Partially	Material handler asks workers if they will need parts, then cuts material or gets parts and brings them over.
Maintain equipment to minimize unplanned stoppages	Yes	Production control rotates equipment for calibration: Equipment has date stickers.

OAP 2 – Assure Seamless Information Flow

Make processes and flows visible to all stakeholders	Yes	Chart shows scheduled production vs. actual production - visible to technicians.
Establish open and timely communications, among all stakeholders	Yes	IPT and supervisors have daily meetings.
Link databases for key functions throughout the value chain	Partially	Working to create a computerized system for quick tracking and documentation.
Minimize documentation while ensuring necessary data traceability and availability	Yes	Standard work sheets reduce the need for detailed documentation. The new computerized system will automate the distribution of information with minimal data entry.

OAP 3 – Optimize capability and utilization of people

Establish career and skill development programs for each employee		Not sure.
Ensure maintenance, certification and upgrading of critical skills	Partially	
Analyze workforce capabilities and needs to provide for balance of breadth and depth of skills/knowledge	Partially	
Broaden jobs to facilitate the development of a flexible workforce	Yes	Operators perform all functions in one area and are no longer limited to one function.

OAP 11 – Ensure process capability and maturation

Define and control processes throughout the value chain	Yes	Guidance sheets are used to control processes.
Establish cost beneficial variability reduction practices in all phases of product life cycle	Partially	Standard work established to ensure all workers use the techniques that have been judged best.

[20] Analysis performed by Dan Dobbs through interviews and observations